An Overview of Radioactive Beam Concepts

John M. D'Auria
Department of Chemistry, Simon Fraser University
Burnaby, British Columbia, Canada V5A 1S6

Abstract

This report presents a status of the field of accelerated radioactive beams (RB). Following a review and comparison of the production methods, a brief description of the various low energy facilities, existing, or proposed, is given with some of the specifications. Emphasis is given to some of the outstanding technical problems existant for the ISOL (isotope separator on-line)/accelerator method of production.

I. INTRODUCTION

It is now well known that ion beams of almost any radioisotope can now be provided by modern accelerators over a wide range of energies and intensities. This has rejuvenated the field of nuclear physics while also providing additional research opportunities for other related disciplines including condensed matter physics, atomic physics, nuclear medicine and surface physics, among others. In this report a brief review of the methods of production will be given as well as a summary of the various facilities (existing and proposed) around the world. Particular attention will be given to low energy accelerated, radioactive beams facilities including a review of some of the technical challenges still remaining before a major facility of this type becomes operational.

II. METHODS OF PRODUCTION

There are two main methods by which accelerated or energetic beams of radioactive nuclides can be produced, namely, the projectile recoil fragmentation method (PF) and the ISOL/Accelerator approach. In the former, a very energetic heavy ion projectile transverses a thin low Z target material, resulting in the production of a wide range of projectile fragments with momenta similar to the incident beam. These products are emitted into a forward cone, dependent upon the projectile energy and can be captured by magnetic separators while elemental selection is obtained by taking advantage of energy loss in some thick wedge absorber. Additional details can be found elsewhere [1,2]. The ISOL method involves production of the desired radionuclide using energetic low Z projectiles, very low energy, eg., 30 MeV protons or even thermal neutrons. The target thickness is determined by the energy of the primary production projectile, or in some cases, the reaction product recoil range. If a thick target is used, chemical methods lead to the release of the desired product from the target into an ion source. A gas jet system can be used with a thin target and in this case the products recoil out of a thin target; these are transported quickly to an ion source located far from the target. Regardless the resultant ion beam is extracted at some potential, generally less than 60 KeV and mass selectivity is then obtained by using a magnetic mass separator. Elemental (Z) selectivity is obtained by the combination of the target chemistry and the appropriate ion source. In some cases the production projectile only makes a limited number of products. Very high resolution magnetic mass separators can also be used to gain some additional final beam purity. Detailed description of this approach can be found elsewhere [3]. A third method involving transfer reactions with heavy ion projectiles at low energies and a superconducting solenoid to select a desired RB has been used to produce a limited number of beams of modest intensity [4]; this method will not be discussed further.

It is very difficult and can be misleading to provide a thorough comparison of these two very different methods in a brief format. In general PF can provide a wide range of RB of acceptable beams with energies higher than about 30 MeV/u while the ISOL method is better suited for RB with lower energies. Table 1 attempts to summarize some of advantages and disadvantages of each, but it is important to emphasize that indeed these approaches are complementary to each other, and that there is excellent physics to be done using each approach.

Projectile Fragmentation (PF) Facilities

There are a number of facilities in the world based on the PF approach which are either operating or planned. These are listed in Table 2 along with some of the facility parameters; additional information can be found in the indicated reference. These facilities are achieving significant results and have demonstrated clearly the importance of this science.

ISOL Based RB Facilities

At present there are no major operating RB facilities based upon the thick target ISOL method although there are one or two smaller systems in operation or being built. Table 3 presents information on the latter while Table 4

0-7803-1203-1/93$03.00 © 1993 IEEE

Table 1
Comparison of RB Production Methods
(optional conditions)

	PF	ISOL Method
Energy Range (MeV)	50-2000	0.2-10(+)
RB Delivery Time	~μs	≥50 ms
Momentum (%)	1-3	~0.1
Emittance (π mm mr)	~20	0.2-1.0
Production Luminosity	$\leq 10^{35}$	$\leq 10^{38}$
RB Intensities	$\leq 10^{9}$	$\leq 10^{12}$
Beam Purity	moderate	high

Further Advantages

PF	ISOL
No chemical requirements	Wide selection of RB
Simple production target	Easy energy variation
High collection efficiency	RB energies ≥0.2 MeV/u
Reliable operation	
Wide selection of RB	
Several major operating facilities	

Further Disadvantages

PF	ISOL
Production target thickness limited.	Intensity dependent on front end chemistry.
Deceleration difficult without losses and requires time.	Decay losses due to target delay.
	Radioactivity contamination requiring remote handling.
	Requires post-accelerator.

Table 2
Projectile Fragmentation Facilities
(existing or planned)

Laboratory	Country	RB Energy	Reference
EXISTING			
RIKEN/RIPS	Japan	100 MeV/u	5
GSI/FRS	Germany	0.5-2 GeV/u	6
GANIL/LISE	France	30-100 MeV/u	7
NSCL/A1200	USA	30-100 MeV/u	8
PLANNED			
CATANIA/FRS	Italy	50-100 MeV/u	9
LNL/ADRIA	Italy	.005-1 GeV/u	10
Dubna	Russia	20-500 MeV/u	11
Osaka	Japan	-	12

Table 3
ISOL Based RB Facilities
(existing*/funded)

Facility	Country	Production System	Post Accel.	Ref.
RIB/ Louvain*	Belgium	K=30 cyclotron Ep=30 MeV	K=110 Cyclotron	13
RIB/ Oak Ridge	USA	K=105 (ORIC) Ep≤80 MeV	Tandem (25 MV)	14
INS/ JHP prototype	Japan	K=68 cyclotron Ep=45 MeV	LINACS (RFQ,DTL) E≤1 MeV/u	15

Table 4
ISOL Based RB Facilities
(planned/proposed)

Facility	Country	Production System	Post-Accel.	Ref.
Arenas[3] Louvain	Belgium	K=110 cyc. (p,d,He)	SC LINAC	18
ISOLDE PRIMA	Swiss	Ep=1 GeV	LINACS	18
RAL	UK	Ep=0.8 GeV	LINACS/ISIS	18
RNB/ Moscow	Russia	Ep=0.6 GeV	LINACS or cyc.	18
PSI	Swiss	Ep=.59 GeV (gas-jet)	K=120	19
GANIL	France	H.I/100MeV/u	K=265	18
INFN/ Catania	Italy	H.I/50-80 MeV/u	Tandem (15 MV)	18
PIAFE Grenoble	France	n_{th} (Reactor)	K=88/160	18
ISAC/ ISL/TRIUMF	Canada	Ep=0.5 GeV	LINACS	20
Argonne	USA	E(^{12}C)=1 GeV	LINACS	21
KEK/ JHP	Japan	Ep=1 GeV	LINACS	15

indicates the facilities in the proposal or planning stage. Detailed information can be found in the indicated reference.

Given the availability of operating PF facilities providing high energy RB and the lack of a major ISOL based system providing high intensity, low energy Rb, the focus of the remainder of this report will be on aspects of the latter systems.

Post-Accelerators for ISOL Facilities

There are a range of options available for accelerating the extracted radioisotopic ion beams from an ISOL system. At Louvain-la-Neuve where one of the first low energy beams was produced [13], a K=110 cyclotron was used to accelerate the first radioactive beam, ^{13}N. While there were some losses on injecting and extracting, nevertheless the cyclotron also acted as a high resolution mass spectrometer allowing for the separation of the desired beam of ^{13}N from the interferent, ^{13}C. The final beam energy was of the order of 1 MeV/u. At Oak Ridge a project has been funded to couple a front end ISOL device to a 25 MV Tandem accelerator [14]. The radioactive species are produced using the K=105 (ORIC) cyclotron, extracting them using ISOL technology, using a charge exchange cell to produce the needed negative ion beam and then accelerating these ions to energies of the order of 5 MeV/u. Chalk River (AECL) is also considering using a 30 MeV primary production cyclotron and a Tandem post-accelerator. This first stage can then be coupled to the TASCC superconduc-ting, high energy heavy ion cyclotron [22]. A number of laboratories are proposing the use of LINACS to provide the required acceleration. The ISL project calls for a combination of room temperature and superconducting LINACS as does the proposed ISAC facility at the TRIUMF laboratory in Canada [20,23]. Such devices are generally more user friendly and forgiving; essentially 100% of the beam is transmitted in the absence of any strippers. The first stage of such systems will need to include an RFQ LINAC to capture the low velocity (β=0.0015), heavy ions (q/A < 1/60) from the ISOL device; the velocity will also vary according to the mass. As mentioned below some study is needed to develop an efficient means to adjust the input velocities, given the need for constant injection velocity when using LINAC's. Demonstration of such an operating RFQ especially CW would be useful and studies are in progress at Argonne and TRIUMF.

III. TECHNICAL AREAS REQUIRING RESEARCH AND DEVELOPMENT STUDIES

While there do exist major PF facilities actively performing physics studies, there is still not a major ISOL based system. Aside from the obvious financial restraints, there do exist some technical questions which require attention before a final system can be designed in detail. The smaller ISOL based facilities, while clearly clarifying important aspects, do not need to address some of the questions the design of a larger facility will precipitate. It should be noted that a number of these questions that an ISL facility will introduce were discussed at a special workshop held last year in Oak Ridge, and the proceedings will be available shortly [24] to provide further details than given below.

A. Primary Accelerator

The tentative specifications for the ISL foresee a primary beam accelerator for light ion (mainly protons) in the energy range of 0.5 to 1 GeV with a current of at least 100 μA. There are two accelerators in North America that can meet these specifications: LAMPF and TRIUMF. In the event that the ISL is not sited at these laboratories, a new primary beam machine would have to be built. This opens up different options and could include an isochronous H+ cyclotron, a FFAG (Fixed Field Alternating Gradient) machine, a ring cyclotron, or a fast cycling synchrotron. Less attractive options would be an H- or superconducting cyclotron or a LINAC for protons, although the latter accelerator is being considered as a source of high intensity, light ions such as ^{12}C [21].

B. Using High Intensity Production Beams

An important aspect to produce high intensity RB is to use high intensity, production beams. This introduces severe problems especially when these are projectiles with energies higher than a few hundred MeV. Beam heating in the target (as well as cooling) is not straightforward when dealing with beam currents up to 100 μA. In addition residual radioactivity levels, and potential contamination possibilities require hard solutions for these and for the problems associated with apparatus failure in high radiation fields and shielding needs to reduce external fields. Similar conditions do exist at present meson facilities, and relevant technology does exist. Joint projects are in progress at TRIUMF [25], LBL [26], and RAL [16] to demonstrate the operation of a thick target, ISOL device in a high intensity proton beam, and to explore solutions to the development of a fail-safe, remote handling system. From another perspective LAMPF is exploring the use of a thin target facility coupled to a gas jet transport system in proton beam currents of the order of milliamps [17]. This would minimize the radioactive contamination problems as well as reduce the shielding needed.

C. ISOL Ion Source Technology

Ion source systems are clearly important although a good deal is already known from considerable developments at the ISOLDE facility. Until now, ISOL devices have produced only single charged ions, but multiple charged ions would be invaluable to minimize the cost of the post-accelerator. ECR (Electron Cyclotron Resonance) sources do produce such multiple charge beams efficiently, and there exists two such sources on-line at ISOL type systems at the TISOL facility [27] and at Louvain-la-Neuve [13]. Considerably more time must be devoted to systematic studies with such systems to understand more about this application and to develop the optimum system. Another new area of ion source technology developments is in the area of ISOL based, laser ion sources [28]. These can provide very pure radioisotopic ion beams and more information is needed on the universality of the approach as well as efficiency measurements.

D. Post-Accelerators

At present it is accepted that the LINAC is the optimal device to post accelerate the radioisotopic ion beams to some desired final energy. LINACs demonstrate high transmission and also the final energy can be increased at a later date in a straight forward manner. Given appropriate funding, this would be the preferred accelerator for the post accelerator of a major RB facility.

The low velocity ($\beta > 0.0015$) ions produced by the ISOL device will have q/A ratio of at least 1/60 if not as small as 1/240. It is believed that the best device to capture and provide some acceleration is an RFQ LINAC. While an 2.1 m in length prototype RFQ has been shown to accept low beta ions (with a q/A of 1/30 and 1 keV/u) [29], further developments are needed. This device was a split vane RFQ, operating with a duty factor of about 10%. CW operation would be preferred to optimize transmission. In addition the front section of the RFQ required operation at a variable high potential to compensate for the varying masses of the different ions that come from the ISOL device. Finally there is a question about whether the LINACs including the RFQ should be superconducting or room temperature. With the technology developments around the world, it appears that SC LINAC structures are becoming more standard, but the RFQ does pose a challenge. Projects are initiating both at TRIUMF [30] and Argonne [31] on some of these questions.

IV. CONCLUSION

The field of radioactive beam science is now developing at an accelerating pace and has allowed the possibility of planning for experiments previously considered impossible. In turn, there is a strong need for more research and development studies in areas previously not considered important. A large number of scientists are quite interested in performing experiments with radioactive beams and accelerator scientists and engineers are strongly encouraged to turn their attention to addressing some of the questions being asked.

V. REFERENCES

[1] G. Münzenberg, *Nucl. Instru. Meth.*, B70, 265 (1992).

[2] B.M. Sherrill, *Proc. of 2nd Int. Conf. on Radioactive Nuclear Beams*, Th. Delbon ed., Louvain-la-Neuve, August 1991, p.3 (Adam Halger, 1992).

[3] H.L. Ravn, *ibid*, p.85.

[4] F.D. Becchetti, et al., *Nucl. Instru. Meth.*, B56/57, 554 (1991).

[5] T. Kuber, et al., *Nucl. Instru. Meth.*, B70, 309 (1992).

[6] H. Geissel, et al., *ibid*, B70, 286 (1992).

[7] R. Anne and A.C. Mueller, *ibid*, B70, 276 (1992).

[8] B.M. Sherrill, et al., *ibid*, B70, 298 (1992).

[9] E. Migneco, et al., *Int. Workshop on Physics and Techniques of Secondary Nuclear Beams*, p.341 (Editor, Prentice, 1992).

[10] G. Bisoffi, et al., *ibid*, p.437.

[11] Y.T. Ognessian, *ibid*, p.377.

[12] T. Shimoda, et al., *Nucl. Instru. Meth.*, B70, 320 (1992).

[13] P. Van Duppen, et al., *Nucl. Instru. Meth.*, B70, 393 (1992).

[14] J.D. Garrett and D.K. Olsen, "A Proposal for Physics with Exotic Beams at the HHIRF", Physics Div, ORNL, Feb. 1991.

[15] T. Nomura, et al., *Nucl. Instru. Meth.*, B70, 407 (1992).

[16] J.R. Bennett, Rutherford Appleton Lab, private communication, *Nature*, 362, 278 (1993).

[17] D. Vieira, LAMPF, private communication.

[18] H. Ravn, et al., "Comparison of radioactive ion beam intensities produced by means of thick targets bombarded with n,p, and heavy ions", CERN preprint; to be submitted to *Nucl. Instru. Meth.*

[19] H. Giggeler, et al., *Int. Workshop on Physics and Techniques of Secondary Nuclear Beams,* Dowdon, France, (Edition Frontiers) p.419 (1992).

[20] L. Buchmann, et al., *Nucl. Instru. Meth.*, B26, 151 (1987).

[21] J. Nolen, private communication.

[22] H. Schmeing, private communication.

[23] "The IsoSpin Laboratory, Research Opportunities with Radioactive Beams", *LALP*, 91-51.

[24] *Workshop on Production and Use of Intense Radioactive Beams at ISL*, Oct. 1992, proceedings to be published.

[25] J. D'Auria and J. Beveridge, private communication.

[26] M. Nitschke, private communication.

[27] L. Buchmann, et al., *Nucl. Instru. Meth.*, B62, 521 (1992).

[28] H.L. Ravn, *Nucl. Instru. Meth.*, B70, 107 (1992).

[29] S. Arai, et al., *ibid*, p.414.

[30] H. Schneider, private communication.

[31] K. Sheppard, private communication.