RADIOACTIVE BEAM FACILITIES: A WORLD VIEW

John M. D'Auria
Department of Chemistry
Simon Fraser University, Burnaby, B.C., Canada V5A 1S6
and TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Abstract

Technological advances coupled with unique scientific opportunities are propelling the establishment of a new technique for nuclear science, namely the use of energetic radioactive heavy ion beams. Facilities now exist which can produce energetic radioactive beams (RB) in intensities and energies sufficient to perform nuclear reactions. Brief descriptions are given of all such energetic RB facilities in the world (operating, under construction, or proposed) which produce beams using either the projectile fragmentation method (PFM) or the ISOL (isotope separation on-line) approach coupled to a post-accelerator. An indication of some of the scientific opportunities is also presented along with some of the anticipated technical difficulties with the ISOL approach.

I. Introduction

Unstable radioactive nuclei have been available in the form of ion beams from on-line isotope separator devices (ISOL) for about 30 years [1]. Within the last few years technological advances have allowed the possibility not only to boost the energy of these ion beams to energies about the coulomb barrier, but also to use different production methods to obtain radioactive beams with energies in the range of 100 MeV/u and higher. The purpose of this report is to provide a brief description of the techniques used to produce energetic radioactive beams (RB), to briefly mention some of the scientific opportunities now available, to give a brief summary of all RB facilities in the world (operating, under construction, or being proposed), and to indicate some of the anticipated technical difficulties with the ISOL approach.

II. Scientific Opportunities with Radioactive Beams

Stopped radioactive beams have been available for many years and important studies completed on the properties of the separated nuclei, or utilizing some aspect of their particular decay to perform studies in material science, atomic physics, nuclear medicine, and related applied areas. Such studies will continue with the added feature of greatly increased intensities due to the new production methods being developed. Properties of nuclides near to and at the drip line can now be studied and of even greater importance, the higher intensities allow measurements of high precision which can critically test predictions of the Standard Model in a search for New Physics.

Energetic, intense RB are now able to initiate nuclear reactions which opens up a wide range of important studies, particularly in the areas of nuclear astrophysics (explosive phenomena, studying the solar neutrino flux problem), new nuclear structure phenomena (nucleon halos), nuclear reaction mechanisms (sub-coulomb barrier fusion), production of very heavy elements, material science (ion implantation, perturbed angular correlation), and many more. The higher energy and intensity of these beams makes determination of the existence of a nuclide close to the drip line, a straightforward measurement.

Typical of the studies possible include the recent observation of the long sought for nuclide, ^{100}Sn [2], the measurement of the rate of the astrophysically important ^{13}N(p,γ)^{14}O reaction [3], the observation of the neutron halos in very neutron rich, light nuclei [4], and the mapping of the drip line in the low Z region [5].

A number of workshops, conferences and symposia have been held on the research opportunities with RB [6,7,8] and a number of the facilities have been designed with particular studies in mind. It is clear that a rejuvenation of the field of the science of the nucleus is occurring. RB facilities can be used to probe the nature of matter in many ways, and further, there are a number of applications of these studies in related fields.

III. Production of Radioactive Beams

A. Overview

Radioactive beams can be produced using different projectiles (protons, neutrons, heavy ions) and a wide variety of nuclear reactions including fission, spallation, fragmentation (target, projectile), fusion evaporation, deep inelastic collisions, and nucleon transfer reactions. Many different facilities using a variety of techniques have been constructed and used over the last 30 years. Each production method has its range of applicability and limits. The approaches which have the greatest success in producing the widest range of radioactive species are high energy, light ion nuclear reactions (such as proton induced spallation, fragmentation and fission) and heavy ion projectile fragmentation utilizing very energetic projectiles. The need to select and separate the species of interest from those produced and to deliver these as a usable beam in an experimental area has led to the two main approaches used today for intense energetic, radioactive beam production. These are the ISOL technique in which radioactive species are produced in a target, transferred by diffusion to an ion source, with an ion beam extracted, and the Projectile Fragmentation Method (PFM). The latter requires only one accelerator and is characterized by a peripheral interaction of the energetic projectile with the target nucleus that leaves the fragment with much of its initial momentum and some angular spread [5]. The ISOL approach requires a second accelerator to boost the energy of separated radioactive ion beams.

B. Comparison

It is very difficult and can be misleading to provide a thorough comparison here of these two very different methods. Table 1 summarizes some of the advantages and disadvantages of each, but it should be emphasized that these approaches are complementary to each other with PFM being the method of choice when requiring very energetic RB (> 30 MeV/u) and the ISOL method when needing intense beams of lower energy (0.1 - 30 MeV/u).

TABLE 1
Comparison of PFM and the ISOL Approach

	PF	ISOL Method
Energy Range (MeV)	50-2000	0.2-10(+)
RB Delivery Time	~ μs	≥ 50ms
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

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

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.

C. Post-Accelerator Options

The options for post acceleration of ISOL produced beams include tandems, cyclotrons and linacs. A tandem seems an attractive option as it is well matched to the DC low energy beams available, has a low energy spread and easy energy variability. With this well known technology, ions up to about mass 80 could be accelerated up to energies of the order of 5 MeV/A. Unfortunately, only negative ions can be accelerated and these must be stripped in the high voltage terminal. The efficiencies of negative ion production and losses on stripping will limit the application of this accelerator option. A cyclotron presents the attractive feature of simultaneously accelerating and mass separating the beam. However, the final beam energy is proportional to the square of the charge to mass ratio of the accelerated ions and high charged state ions are required to realize this option for cyclotrons of reasonable size. It is also difficult to obtain a wide range of energies needed for certain types of studies. The combination of a linear accelerator (LINAC) preceded by a radiofrequency quadrupole (RFQ) bunching and preacceleration section as proposed initially for TRIUMF [10] seems the most attractive option for post acceleration of presently available ISOL beams. The RFQ has a large acceptance for the low velocity ISOL ions and produces a beam that can be efficiently matched to a following conventional or superconducting linac. Stripping is needed at about 100-300 keV/A in order to keep the cost of the LINAC reasonable. A summary of the production beam and accelerator options is given in Table 2 (shown on following page).

IV. Radioactive Beam Facilities in the World

A. Overview

At present there are at least four operating PFM high energy radioactive beams facilities, and one operating accelerated RB facility of the ISOL type. For purposes of subsequent discussion ISOL facilities which have not proposed accelerating the extracted ion beam are not included. For most laboratories the approach is to adapt older but available accelerator structures to become operational quickly and for a reasonable cost. Additional information on some of these facilities is given below, while more detailed material can be found in references [1], [5], [7] and [9].

TABLE 2
Production Beam and Accelerator Options

Production Beams	Post Accelerator
Thermal Neutrons -high cross sections for fission products -limited mass range -target/source technically difficult -high power density in target	Tandems -accepts DC ISOL beams -variable energy up to ~5 MeV/u -must inject negative ions and strip restricts species available charge exchange channel/ low efficiency
Light Ions (~100 MeV/A) -high cross sections (especially light neutron rich elements) -short range high power density in target -limited beam intensity	Cyclotrons -CW beam operation -high mass resolution -cost effective heavy ion accelerato -energy variation time consuming -require high charge state at injectio low production efficiency -poor transmission efficiency
Low Energy Protons (30-100 MeV) -high beam intensities available -production close to target mass reactions (p,n)(p,α)(p,2p) (p,pn) may require enriched targets -short range high power density in targets	RFQ Linac -accepts DC ISOL beams -requires low β RFQ (limited mass range for q = +1) -q/A must be increased before the linac stripping usually required -good transmission -energy variation possible
High Energy Protons (0.1-1.0 GeV) -high beam intensities available -fission-spallation-fragmentation reactions broad range of nuclei -moderate cross sections -long range/low power density in targets	

B. PFM Radioactive Beams Facilities

1. GSI (Gesellschaft Für Schwerionenforschung), Germany. At GSI RB's are produced through fragmentation of very energetic (.5-2 GeV/u) heavy ion projectiles up to U from the coupled acccelerators, the linear UNILAC (20 MeV/u) followed by the heavy ion synchrotron, SIS. Resultant secondary beams are analyzed in a large zero-degree achromatic spectrometer (FRS) and can be either studied directly, or injected into a storage ring (ESR). Soon, beams from the ESR will be reinjected into the SIS for further acceleration. The FRS uses the energy-degrader technique and a combination of dipoles and quadrupoles to achieve A and Z resolution. Its resolving power is 1.5 x 10^3 for 20 pi mm mr beam emittance. Its production luminosity is $< 3 \times 10^{35}$ cm^{-2} s^{-1}. Cooling is achieved in the ESR ring and fragments possibly decelerated down to 5 MeV/u. Space charge forces in the ring limit the intensity of ions in the ring, and the time of cooling restricts this process to radioactive beams with half lives of the order of seconds.

2. GANIL (Grand Accelerateur Nationale D'Ions Lourds), France. Primary heavy ion beams at GANIL are produced with two K=400 cyclotrons that can be operated independently or in tandem. With stripping in the latter scenario, higher charge states lead to production of beams with final energies from 30 to 100 MeV/u. Radioactive beams are extracted using the zero degree doubly achromatic spectrometer, LISE3. The inclusion of an energy degrader of variable thickness and a crossed electrostatic and magnetic field device, a Wien filter provides excellent isotopic selection in the final RB.

3. RIKEN (Inst. of Physical and Chemical Research), Japan. A variety of energetic (from 20 MeV/u for U up to 135 MeV/u for light ions) heavy ion production beams for the RIKEN RB facility are available from a K=540 separated sector cyclotron injected by either a heavy ion LINAC or an AVF K=70 cyclotron. A doubly achromatic spectrometer (RIPS) is used to analyze the fragment recoils and produce the required energetic RB.

4. NSCL (National Superconducting Cyclotron Laboratory), USA. At NSCL, a wide range of RB in the energy range from 50 to 200 MeV/u are produced using the K=1200 superconducting cyclotron, together with the beam analysis device, the A1200. The latter is an achromatic device with two intermediate images that allows for momentum measurements and the placement of degrader foils. An upgrade of the facility, coupling the available K=500 cyclotron to provide an initial acceleration for a significant increase in final RB intensities and energies is planned.

5. Planned Facilities.

a) LNS (Laboratorio Nazionale del Sud), Italy. A Fragment Recoil Separator (FRS) has been designed for installation at LNS to produce RB using the energetic heavy ion beam (up to 100 MeV/u from their newly commissioned, K=800 cyclotron.

b) ADRIA (Laboratori Nazionali di Legnaro), Italy. A second Italian project at Legnaro involves two accelerator rings which produce heavy ion beams from .8 to 2.5 GeV/u. Energetic RB will be produced by PFM; cooling and deceleration is also planned.

c) TREBle: (JINR-Dubna), Russia. A PFM facility is under construction using two coupled cyclotrons (K=4/K=10) to provide beams of exotic nuclei with A < 50 with energies from a few MeV/u up to 200 MeV/u. A recoil separator (COMBAS), and other systems will be used to analyze and study the fragments.

C. ISOL Based, Accelerated Radioactive Beams Facilities

1. Louvain-la-Neuve, Belgium. Using the K=30 CYCLONE 30 high intensity (500 μA) proton cyclotron as

the production system and the K=110, CYCLONE cyclotron as the booster, this first accelerated RB (^{13}N) was produced here, and now they have 5 additional beams available (^{6}He, ^{11}C, ^{18,19}Ne, ^{35}Ar). An upgrade facility, the ARENAS[3] project has been funded which includes a new booster accelerator to cover the energy range between .2 and .8 MeV/u for (6.5 > A/q > 13). Either of the former cyclotrons can be used for production.

2. HRIBF, Oak Ridge National Laboratory, USA. This facility is under construction and the production system is expected to be tested later this year. The refurbished K=105 ORIC proton cyclotron is the production facility, and following charge exchange, negative ion beams only from the ISOL system will be accelerated with the 25 MV tandem. Beams up to mass 80 will be accelerated from about .5 - 5 MeV/u. The first accelerated RB are expected to be ^{17}F and ^{32}Cl.

3. SPIRal, GANIL, France. As an extension to the PF program, funding was requested and obtained to produce low energy RB using the ISOL method. Projectile fragmentation primarily in a graphite target, but also target fragmentation with different materials using energetic heavy ion projectiles will be used to produce a wide range of products. A K=260 cyclotron will be the booster and the final RB will exhibit energies from 2 to 29 MeV/u. An ECR ion source on the ISOL device is essential to provide the needed high charge state for this booster. A test system (SIRa) is in operation to develop a method to handle the high power density that result from the short range of the heavy ion production beam and to develop an approach to efficiently transfer the produced activity into the ion source.

4. ISOLDE, CERN, Switzerland. The ISOLDE facility has been the premier thick target, ISOL device in the world for about 26 years initially using 600 MeV protons from the synchrocyclotron (SC) and now using 1 GeV protons from the CERN PS-Booster. A wide range of radioactive ion beams in relatively high intensities are available and have been used in an extensive science program mainly in the fields of nuclides far from stability and in condensed matter physics. For a number of years various post-accelerators have been postulated for installation, but very recently it has been strongly suggested that a system similar to the linear accelerator system at Heidelberg will be installed at ISOLDE. This would lead to the acceleration of ions with A/q < 9; coupling of this system with an EBIS (Electron Beam Ion Source) is being studied to extend the mass range that could be accelerated.

5. INS, University of Tokyo, Japan. Some years ago a major radioactive beams facility was proposed as part of a Japanese Hadron Project (JHP). A prototype facility for the E-ARENA area of the JHP is presently under construction at INS. It will make use of the existing K=68 cyclotron as the production accelerator capable of delivering 40 MeV protons (10 fA) on target, as well as some other light ions. Post-acceleration will be done with a split-coaxial RFQ followed by an interdigital-H LINAC. The output energy for species with A/q < 30 is from 200 to 800 keV/u. This is the first RB facility employing LINAC, and while 100% transmission is expected, the duty factor is only 30%.

6. ISAC-1, TRIUMF, Canada. The first formal proposal to couple an isotope separator (TISOL) to a linear accelerator dates back to 1985. Designated ISAC (Isotope Separator and Accelerator), it was sidetracked for many years at TRIUMF by the ill-fated KAON project. A smaller version is in the design phase and will inject RB from an upgraded TISOL facility into a LINAC, resulting in the production of beams with A/q < 30 with energies between 0.2 and 1.5 MeV/u.

7. Excyt, Catania, Italy. This proposed facility, Excyt (EXotics at the CYclotron Tandem) will utilize features similar to that planned at GANIL and at Oak Ridge. Here energetic heavy ions will be the production beams and an ISOL type device will reside on a 150 kV platform. Negative radioactive ions will be produced and accelerated (A < 40) using the available 15 MV Tandem. The heavy ion production beam will simplify the target chemistry for the release of RB of interest as compared to the Oak Ridge approach, and the need for highly charged ions as compared to GANIL is also not present.

8. RNB, Moscow, Russia. In connection with the Moscow meson factory a radioactive beam project is believed under construction to utilize the 600 MeV protons (0.5 mA) as the production beam. A LINAC booster is proposed to be used based on RFQ and inter-digital h-type structures with intermediate stripping. The maximum A/q is proposed to < 60 and the maximum RB energy, 6.5 MeV/u.

9. PIAFE, Grenoble, France. In the proposed PIAFE (Projet d'Ionisation et d'Acceleration de Faisceaux Exotiques), facility thermal neutrons from the ILL (Institut Laue Langevin) reactor will be used to produce radioactive fission products from a ^{235}U target placed close to the core. Singly charged ions of fission products with masses from 75 to 150 produced with standard ISOL sources will be transported 400 m to an ECR ion source to produce multiply charged ions. Mass selected ions can be injected into the SARA accelerator complex consisting of a K=88 injector cyclotron and a K=160 separated sector cyclotron. The aim is to produce RB with energies from 2 to 10 MeV/u. Considerable R & D is needed to study some of the technical problems connected with this proposal.

10. Others. A number of other laboratories are also developing proposals or are involved in related projects.

At ANL (Argonne National Laboratory, USA) the plan is to use a high intensity beam of deuterons from a LINAC to intercept a pre-target to produce a beam of energetic neutrons (100 MeV) which in turn will fission a very thick target of uranium. This will reduce the power density from the production beam in the target. Mass analysed radioactive ions would be produced using an ISOL device and the present LINACs at ANL would be used to boost the energy to around 6.5 MeV/u.

At LAMPF (Los Alamos Meson Production Facility, USA) a He gas jet system has been installed to study its efficiency to transfer a wide range of products produced with the 1 mA, 800 MeV proton beam on a thin uranium target. This could eliminate the considerable problems with handling when using a thick target ISOL system. A second phase would be to install an ion source and mass analyser at the collection end of the gas jet system to produce radioactive ion beams. A booster accelerator can then be coupled to produce energetic RB.

At RAL (Rutherford Appleton Laboratory, England) an experiment has been funded to study the operation of a thick target ISOL device in a very intense (100 fA) 800 MeV proton beam. This test will compare the yields of radioactive species from a Ta metal target coupled to a surface ion source and a mass analyser, to those measured at the ISOLDE facility.

In North America the ISL (IsoSpin Laboratory) steering committee has put forward the concept of a second generation RB facility for consideration. Rather than using existing accelerators, design specifications have been developed to produce a full fledged facility to meet the goals of most experimental programs. An initial concept of a BenchMark facility would use very energetic, high intensity protons coupled with a thick target ISOL device would produce most radioactive isotopes using known technology. A linear accelerator system would be used to produce RB with energies from 0.2 to 25 MeV/u.

Summary

While there are a number of operating RB facilities using the PFM, there is only one facility producing low energy RB with the ISOL approach. There are a number of facilities planned, proposed or under construction using the ISOL method but several of these have challenging technical problems which must be overcome to make them useful facilities to perform a full experimental program. Given the very full and extensive experimental programs possible at such facilities, and the large number of laboratories around the world interested in playing a role in this field, it is expected that the use of accelerated radioactive beams will be an important technique for many years.

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