Review of radioactive ion beam facilities and research opportunities

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Abstract

This report presents a comparison of the radioactive ion beam production methods and their specifications. An overview of existing or funded facilities is given with some prospects for the future. Radioactive ion beams arise a great enthousiasm among the scientific community since they allow to achieve experiments previously considered impossible in nuclear physics and in other fields of physics. Few typical physic cases will illustrate challenges and perspectives.

"It is my view the continued development and application of secondary ion beam techniques could bring the most exciting results in laboratory nuclear astrophysics in the next decade".

W.A. Fowler, Nobel lecture 1983
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I. INTRODUCTION

In the past two decades, the possibility of accelerating heavy ions allowed a major evolution of nuclear physics[1] in studying extreme states of nuclear matter (temperature, compression, multifragmentation, flow..) and quantum collective effects (high spins, multiphonons resonances, ...). The next step in such an evolution is to use radio-isotopes as projectiles since then, two contrains of nuclear physics are removed : the limitation of the isospin degree of freedom near the statibility valley and the limitation of colliding nuclei in their ground states[2].

There are two main methods by which energetic Radioactive Ion Beams (RIB) can be produced : the projectile recoil fragmentation method (PF) and the ISOL method (Isotope Separator On-Line) followed by a post-accelerator. This report present a brief description of the status of various facilities based on these two methods to produce RIB. The new research opportunities will be illustrated by few physic cases.

II. RIB PRODUCTION BY THE PROJECTILE FRAGMENTATION METHOD

1. Principle

Projectile fragmentation (PF) becomes a significant reaction mechanisms at heavy ion energies from 50 Mev/A to several Gev/A for a wide spread of A, Z and N/Z fragment production ; to use them as radioactive beams and to induce secondary reactions, it is necessary to prepare them even at low (or very low) intensities with similar qualities as for primary beams. Advantages of this method for RIB productions are : simple production target, short separation times (μ sec), reliable operations. The main disadvantages are : poor beam emittance, large energy spread (few %), deceleration up to few Mev/A difficult without drastic lost in intensities, long required time (> 1 sec) for production, target thickeness limited.

Besides the production cross sections, the other key ingredient of the reaction mechanisms which determines RIB rates are the fragment momentum distributions which determine the emittance of the fragment beams[3].

2. Facilities

Experiments using PF techniques have been pionnered at LBL[4] and then at GANIL[5] for more than 10 years. Since this time nearly all accelerator facilities which deliver beams with energies higher than 50 MeV/u have or are planning (table 1) to implement a facility based on fast recoil techniques. A large fraction of research time are devoted to this field presently[6].

Laboratories with such existing facilities or planned are listed in table 1.

Table 1 - Projectile Fragmentation Facilities (existing or planned)

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

One of the biggest problem produced by this technique is that energy and angular spreads of beams are much larger than of a standard beam. The use of profiled degraders to decrease the energy contribute to increase the emittance. A more powerful but coastly method is realized at GSI, where the PF separator FRS is coupled to a storage ring ESR. The time scale for cooling and deceleration from few hundred Mev per nucleon down to 20 Mev/nucleon is of few seconds and hence nuclei with shorter life-time are lost. If deceleration to coulomb barrier energy is required the e-cooling system may also limit the beam intensity to 10^6 sec^{-1}.

3. The SISSI facility at GANIL

The main limitation in the broad range of physics induced through the use of RIB is their weak intensities. Therefore GANIL has put much efforts towards increasing primary beam intensities (2µA particle) on target production. Another requirement is to increase the transmission of the RIB. The device SISSI, in operation since beginning 1994 (fig 1), essentially aims at matching (fig. 1) the rather large opening (2x70-80 mrad) of the emission cone of the fragmentation products to the acceptance of the beam-lines, so that they can be conducted

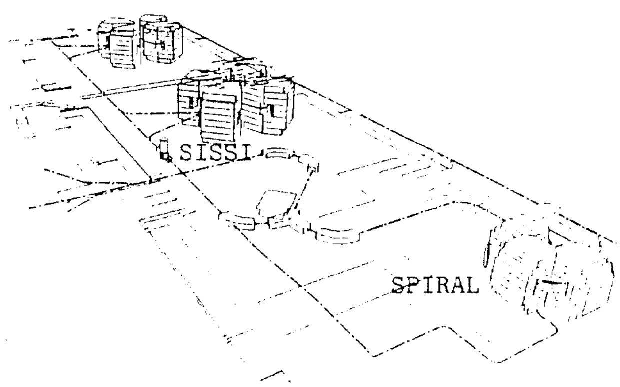

Fig 1. Layout of the SISSI and SPIRAL implantation at GANIL

in any experimental area. To keep these products within an emittance of $\varepsilon_T \approx 16\pi\ mm.mrad$ the Liouville's theorem makes it necessary to keep the beam-spot size under the rather small value of 0.4mm. This can be achieved using magnetic lens ; but since they will be located in a very congested part of the cyclotron hall, very large magnetic fields (11 Teslas) have to be produced. The SISSI device is a set of two superconducting solenoïds (each solenoïd is 800 mm long, with Nb Ti coils and Nb_3 Sn coils) ; the target production is in between. This device has been used successfully beginning 1994 to produce an ^{6}He beam with 10 πmmrad emittance and has allowed the observation of ^{100}Sn isotope with LISE 3 spectrometer by ^{112}Sn fragmentation method.

III - RIB PRODUCTION BY THE ISOL METHOD

1. Principle

The basic principle of this method consists in producing RIB at rest, in a thick target through a nuclear reaction induced by a primary beam high energy proton, intermediate energy heavy ions and thermal neutron as indicated, in fig. 2, for the fission case.

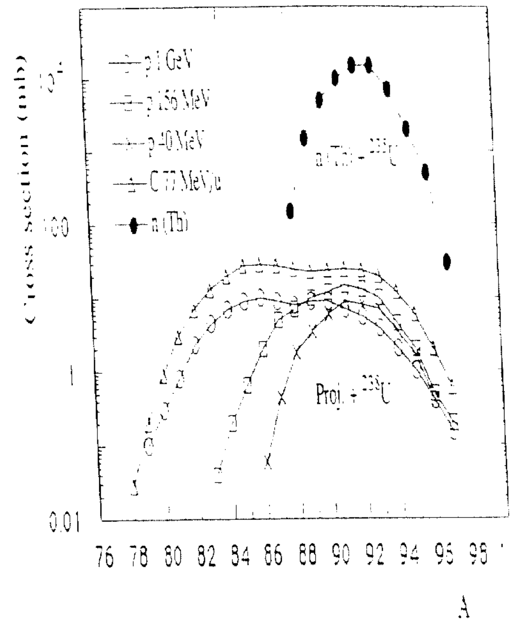

Fig. 2. Fission fragment cross section

Chemical and physical methods are then used continuously to separate the various elements and transfer them into the ion source from where they are ionized and then accelerated through a mass analyzer.

The production rate in the target-source is expressed by $I = \sigma\phi N\varepsilon_1\varepsilon_2\varepsilon_3$ where σ is the production cross sections, ϕ the primary beam intensities, N the target thickness and ε_1 the product release and transfer efficiency, ε_2 the ion source efficiency and ε_3 the radioactive decay losses.

The ISOL technique is complicated by needs of high temperature physics, chemistry, metallurgy diffusion and surface absorption processes which take place in the target-ion source ; all these processes add to the delay time wich results in loss of short-lived (< few seconds) radioactive species.

2. Existing or funded ISOL based RIB facilities

. <u>ARENAS at Louvain La Neuve</u>[7)]

The only existing facility is at Louvain-La-Neuve where ^{13}N and ^{19}Ne RIB are now routinely accelerated. This is achieved by means of a 30 MeV proton beam with few hundred of µA intensities. A flux of 5 10^8 ^{13}N ions/second out of the separator at 0.6 MeV/A is used for study of nuclear reactions of astrophysical interest.

A compact isochronous cyclotron with an energy constant K of 44 MeV (CYCLONE 44) and an energy range of 0.2 to 0.8 MeV/nucleon for the acceleration of light radioactive nuclei (A< 30) is under construction at Louvain-La-Neuve. Its main characteristic lies in the combination of a large overall efficiency (25 % from ion source to experiment's target) with a high resolving power (10^4) for elements with similar M/Q. Radioactive elements are produced using a 30 MeV 500 μA beam from CYCLONE 30 and, in a later stage, using higher energy proton, deuteron, ^3He, ans alpha-particle beams from CYCLONE. First beams are expected in 1996.

. The OAK RIDGE radioactive ion beam facility[8)]

Garrett et al and Olsen et al proposed based on the experience from the USINOR one line mass separator to use the ORIC cyclotron which could deliver 80MeV proton for the production system and then to use the Tandem (25 MeV) as post accelerator. The challenging point is to convert radioactive atoms into negative ions with reliable efficiency for this process.

This facility is constructed to deliver proton-rich RIB above coulomb barrier for A < 80 and will be in operation in 1996.

. SPIRAL at GANIL[9)]

(Separateur et Post-accelerateur d'Ions Radioactifs Accélérés en Ligne)

This project called SPIRAL has been funded, and a realization within five years is planned. A lay-out of the facility is presented in fig. 1.

Basic features

- Use of heavy ion beams $\left({}^3He\ to\ Ar\right)$ from the GANIL facility (5×10^{13}light ions/s at 95 MeV/u) as a primary beam to produce radioactive atoms, from the interaction of this beam on a thick target.

- An ECR source as an ionizer, produces multicharged ions with a high yield (ratio between the number of extracted ions with the required charge state and the number of atoms injected into the source). The ionization efficiency for the most probable charge states are the following : 60 % for Li, 25 % for Ar and 15 % for Pb. The highly radioactive environment in the vicinity of the target implies the design of a coil-free ion source (only permanent magnets) : GANIL handles this technique fairly well since few years. Because the short range of heavy ions in matter, a great deal of power is deposited in a very small volume $\left(1p\psi A\ of\ {}^{12}C\ at\ 95\ meV\ /\ A\ produces 3KW\ /\ cm^3\right)$. In a first period only few materials will be used for targets and RIB will be based primarily on projectile fragmentation rather than on target spallation).

- Previous to injection into a post-accelerator, an efficient selection spectrometer of ions is required. An additional selection is provided by another analyzer located after the accelerating system.

- our choice of a compact cyclotron as post accelerator is based on the following main reasons : first of all, using a high charge state ion source allows us to consider a cyclotron as the most economical solution and second, the energy range to be covered (≅ 2 to 20 MeV/A) for the charge over mass ratio as given by the ECRIS (≅ 0.1 to 0.62) are typical of a compact cyclotron whose beam characteristics satisfy rather well requirements of physicists. Moreover, a cyclotron is by itself a powerful mass analyser and will deliver rather pure beams, which is a prime quality in RIB physics. Third, GANIL has a good knowledge of cyclotrons and a long experience in their design and operation.

At last and not least, this new facility will fit in the loose end of the existing building still lowering the cost of an already rather cheap solution. First beams are expected in currently 1998. An International Scientific Committee has been installed to pilot the project and also to organize a new european user laboratory for radioactive beams at GANIL.

3. Proposed ISOL based RIB facilities

. ISOLDE-PRIMA[10)]

After 23 years of operation on-line to the CERN, 600 MeVprotons SC, a new site is now at the CERN (PS). Many intense low energy RIB have been produced in the past and a project is under consideration to accelerate them. A RFQ plus linac arrangement is favoured and this accelerator will accept q = 1 ion and will have an energy range up to 5 MeV/A for A ≤80. At present, the physics program is based only on 60 keV RIB. This ISOLDE system which involves no major extrapolation of existing technology and is being used as the model for the second generation machine in Europe with ISIS (RAL[11)]) or in USA with Isospin Laboratory project[12)]. The proposal for the ISOLDE post-accelerator is currently being written.

. The EXCYT facility[13)]

The INFN at Catania plans to construct a RIB ISOL facility based on the K = 800 superconducting cyclotron. Accelerated light ions up to 100 MeV/A will be transported on a thick target placed on a 150KV high voltage platform to produce RIB. The recoil fragment attached to aerosols will be carried out to a negative ion source and then extracted as 1^- ions. They will be accelerated by the 15 MV MP tandem to energies up to 8 MeV/A depending of the masses with intensities up to 10 ppA.

. The PIAFE project[14)]

Fission fragments produced in the high thermal neutron flux of the ILL reactor will be accelerated by the SARA cyclotrons. The method consists in placing few grams of ^{235}U target material in a neutron flux density of $10^{12}/sec*cm^2$ or larger. The most easily extracted and ionized nuclei wil be alkalines and rare gas. Different possible targets arrangements with different ionization schemes are considered. After acceleration around 20 kV, the single charged ions should be mass analyzed in a standard mass spectroscopy outside the reactor shield. The single charge ion would be transported under vacuum up to the SARA site when they would be injected into the ECR source via a heated catcher. Post accelerations are insured by the two SARA cyclotrons. R and D work has been started on different aspects of the project.

Some of the caracteristics of the planned and proposed facilities are listed in table 2 and fig. 3.

Table 2 - From ref 15)

Isotope	ARENAS	CATANIA	CERN	GANIL	PIAFE
^{11}Li		$2 \cdot 10^3$	$1 \cdot 10^4$	$2 \cdot 10^4$	
^{13}N	$7 \cdot 10^{10}$		$4 \cdot 10^9$	$6 \cdot 10^9$	
^{15}O	$2 \cdot 10^{10}$	$5 \cdot 10^8$	$2 \cdot 10^9$	$4 \cdot 10^9$	
^{17}F		$1 \cdot 10^9$	$8 \cdot 10^7$	$1 \cdot 10^9$	
^{19}Ne	$3 \cdot 10^{10}$		$1 \cdot 10^{10}$	$1 \cdot 10^9$	
^{20}Na		$9 \cdot 10^6$	$4 \cdot 10^8$	$1 \cdot 10^8$	
^{34}Ar	$3 \cdot 10^9$		$4 \cdot 10^7$	$1 \cdot 10^8$	
^{78}Zn			$7 \cdot 10^4$	$1 \cdot 10^5$	$1 \cdot 10^3$
^{73}Se		$3 \cdot 10^8$	$5 \cdot 10^8$	$2 \cdot 10^8$	
^{94}Kr	$5 \cdot 10^7$			$9 \cdot 10^7$	$8 \cdot 10^9$
^{105}Cd				$1 \cdot 10^5$	
^{132}Sn				$3 \cdot 10^5$	$1 \cdot 10^6$
^{144}Xe				$5 \cdot 10^4$	$1 \cdot 10^7$

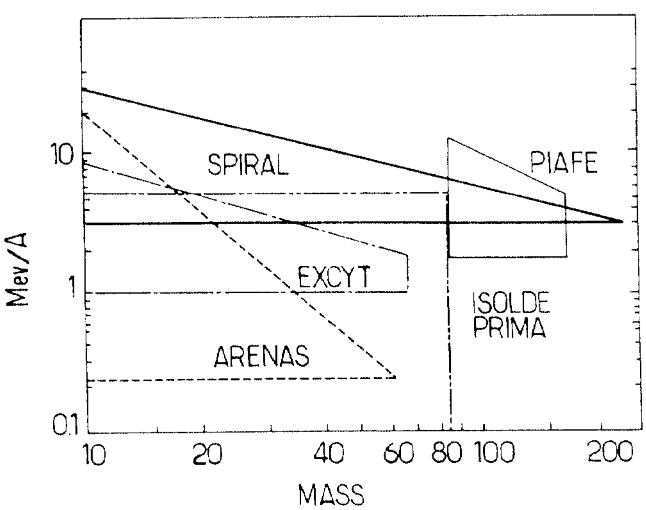

Fig. 3 - Comparison of the different ISOL facilities.

IV - SCIENCE WITH RIB

Heavy ion research with RIB is a young branch of nuclear physics and exerts a growing impact on many other fields of science. We will discuss few examples :

1) Nuclear Physics :

the scientific impact of RIB is related to the fact that they remote two major constraints which limit so far our view of nuclear structure.

i) The confinement of target and projectile in the limit of stability. RIB allow to reach new landing spots under unusual conditions of excitation energies, angular momentum and isospin.

ii) The possibility to use isomeric excited states : such beams permit to construct excited states with a vacuum different of the usual ground state.

These two aspects lead to what has been called "Renaissance de la structure nucléaire". Among the specific and new topics open by RIB, we can mention :

a) Production of new ternary nuclei. The large disymmetry for the number of protons and neutrons in both target and projectile allow to produce unusual ternary nuclei by nuclear reaction. Then new shape transitions and high spin states as well as new magic shell numbers could be reach (fig. 4). More generally the variation of the number of valence nucleons as well as their occupied orbits open a virgin field of studies of residual interactions.

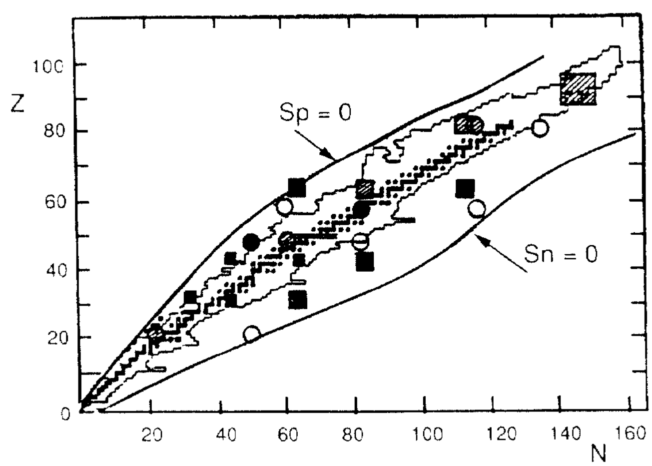

fig. 4 : Most of the area between proton (Sp=0) and neutron (Sp#0) drip lines are accessible to investigation with radioactive beams. New landing spots are indicated for nuclei with superdeformation (black squares and open) and hyperdeformation (black circles and open). From ref 9.

b) Projectile excitation

The matter distribution and its collective modes can be studied so far only for nuclei in the stability valley.

When producing, unstable isotopes with a lifetime larger than 1μsec, it becomes possible by different reaction mechanisms to study the nuclear properties of these transient states.

c) Isomeric beams

In general such a state is a simple particle-hole configuration with a rather long lifetime and then its matter distribution is quite different of the ground state. The study of elastic and inelastic of such level will allow to open a new avenue of nuclear structure. Furthermore the possibility to study the collisions of excited target nuclei (ie ^{178}Hf 16+) by an isomeric beam (i.e ^{42}Sc 7+) is a fascinating possibility to get information on spin-isospin interaction.

2) Nuclear astrophysics

Nuclear reaction involving exotic nuclei play a crucial role in stellar evolution, for energy production and nucleosynthesis. The r-p process describes a sequence of proton capture reaction which occurs within the very short time scales which involve proton-rich radioactive nuclei. This process is blocked by proton instability or by beta decay lifetime. Hence, nuclear levels, cross sections, nuclear decay energies and nuclear decay paths are few examples of quantities, which play a role in astrophysical models. Because nuclei of extreme composition exist in stellar environment, an understanding of their properties is a challenge for the nuclear physics community.

3) Solid state physics

In condensed matter physics, RIB could be used as a local (probe) at the atomic level to study defect properties of materials. The method consists to implant RIB in the material with low fluences which do not transform too much the studied site. Then research on surfaces, semi conductors, organic or biologic matter becomes accessible to nuclear physics methods. Because of low fluences, the residual radioactivity remain weak after the caracterisation of the material. It is more efficient to implant RIB in matter than to create them by irradiations with stable projectiles. It is the only method accessible with low Z material.

V. SUMMARY

In this review, we tried to show the relative merits of the RIB production methods. We described mainly the funded facilities and those which are complementary from each others. The project SPIRAL is the most versatile for the first generation RIB machine taking into account also for the well equipped experimental area. A great deal of R and D efforts have to be achieved in near future on the target-source system in order to overcome dificulties related to RIB production efficiency. So far, exotic nuclei appears as objects for investigations but with the opportunity to accelerate them with qualities comparable to usual ion beams, they open new doors for research in nuclear physics, astrophysics and material science. The knowledge from studies with first generation and R and D facilities will serve as the foundation for the eventual construction of a second generation facility in Europe or elsewhere.

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