REVIEW OF RADIOACTIVE ION BEAM ACCELERATORS

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Abstract

During the last decade there has been a growing world-wide interest in the possibility of using radioactive ion beams for a variety of fundamental studies in pure and applied science. The possibility of producing intense beams of radioactive nuclei with extreme neutron to proton ratio (N/Z), compared with natural isotopes, has opened a new era in nuclear science. This interest has been generated by the considerable improvements which have occurred over the past 30 year in the field of heavy-ion accelerators, ion source, more particularly, in on-line production and isotope mass separation. The three major techniques used to produce intense radioactive ion beams are the in-flight separation method (IFS), neutron fission product using reactor (NF) and the on-line isotope separation (ISOL). Coupling very intense production sources of unstable nuclei to efficient accelerator structures will lead to the availability of a wide range of nuclei far from stability. This paper reviews the properties of radioactive ion beam accelerators in operation, under construction and proposed around the world.

1 INTRODUCTION

We are at a turning point in the history of nuclear physics. For the first time we can use and expect to use intense radioactive ion beams (RIB) along a very large neutron or proton line for systematic nuclear studies. With the new intense RIB facilities under construction and upgrade of existing facilities it will be possible to have access to new neutron and proton shell closures, and then to test the nuclear shell model. In the past, nuclear reaction studies were restricted to the use of stable nuclear projectile. New dimensions of nuclear physic were introduced because of the development of RIB facilities. Nuclear reactions with RIB of light neutron-rich like ^{11}Li and ^{11}Be led to the discovery of the halo structure of their neutron distribution [1, 2]. A similar structure of the very loosely bounded valence proton was also discovered [3].

This paper covers mainly the new ISOL based RIB facilities and major upgrades of RIB facilities based on in flight separation using the Projectile Fragmentation.

2 PRODUCTION METHOD

2.1 In-flight separation using the Projectile Fragmentation

The projectile fragmentation method is a very powerful method to produce a large variety of intense Radioactive Beams at heavy ion beam energies of ≈ 50 A*MeV to several A*GeV. The production mechanism is characterized by peripheral interaction of the projectile with the target nucleus that leaves the fragment with much of the initial momentum and with a small angular dispersion. This reaction mechanism produces a wide variety of nuclei with a large spread in A, Z and N/Z ratios. Before being useful for any experiments, the RIB has to be purified using several steps: magnetic separator, differential energy loss and velocity filter.

A variation of this method is used at the Michigan state university [4]. Due to the production mechanism this method is limited to RIB close to the stability line.

2.2 The ISOL method

The ISOL method uses a complementary approach to the projectile fragmentation. A high energy beam of light particles (p, d, ^{4}He or n) impinges on a heavy target and produces radioactive nuclides via spallation, induced fission, target fragmentation. The recoils are stopped in the target that is brought to a very high temperature in order to favor the release of radioactive atoms. They diffuse to the surface from which they desorb and then enter an ion source to be ionized.

ISOLDE at CERN [5] is the major example of a facility based on this technique. There are also other facilities using low energy proton beams such as Louvain-la-neuve [6] or heavy ions as the primary beam for RIB production.

2.3 Comparison of the production method

The two major production techniques can be viewed as complementary methods. Each one has advantages and disadvantages. Table 1 gives a summary of advantages and disadvantages for both production methods.

3 ISOL BASED FACILITY

3.1 Louvain-la-neuve

Since the first successful acceleration of ^{13}N in 1989, Louvain-la-neuve has led the way in the field of RIB acceleration, and considerable progress has been made since then [7]. Now the range of post-accelerated ion species spans from ^{6}He to ^{35}Ar. The intensities range from 10^5 pps for $^{35}Ar^{5+}$ and up to $2x10^9$ pps for $^{19}Ne^{2+}$. The energy range now available is between 0.6 to 4.9 A*MeV.

The Louvain-la-neuve facility uses two cyclotrons, and an on-line ECR ion source to produce, ionize and accelerate the radioactive ion beams. The 30 MeV proton beam of the first accelerator, CYCLONE30, is used to produce a large quantity of unstable elements using suitable targets. These elements are injected into an ECR ion source, they are ionized, and after a first magnetic separation, are injected into a second cyclotron, CYCLONE110, which accelerates the beam to the required energy.

The exotic species accelerated so far are mainly noble gases such as ^{6}He, ^{18}Ne, ^{19}Ne, ^{35}Ar, or elements like ^{13}N or ^{11}C which are extracted on-line from the production target, in gaseous form like ^{13}N-N or $^{11}CO_2$ molecules. Due to the quite low energy of the production beam those elements have to be produced using specific targets. The production beam intensity varies between 120 µA and 180 µA, depending on the target material of the charge state required since the target is directly connected to the ECR ion source.

^{18}F is a peculiar case in this list because it is produced by a quite different approach. Due to the high chemical reactivity of this element, the on-line extraction of fluorine from the production target with a high efficiency is difficult. They were successful by using a technique developed by the PET center. After chemical separation the

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$CH_3{}^{18}F$ is transferred in a gaseous form to the ECR ion source.

Table 1. Advantages and disadvantages of the In-flight separation method

Method	Advantages	Disadvantages
in-flight Separation	• Short separation (micro sec.) • Simple target fabrication • High collection efficiency (app. 50%)	• Low primary beam intensity for heavy ions • Target thickness limited by momentum acceptance of the recoil spectrometer • Moderate beam purity, required several stages • Large emittance; transverse and longitudinal • RIB at high energy, difficult to decelerate
ISOL	• Thick Target • Intense Primary Beam are available, highest luminosity • High RIB purity • Low emittance; transverse and longitudinally • Long expertise in the field or target/ion source	• Yield strongly coupled to target/product chemistry, (element dependent) • Delay due to diffusion, desorption and effusion time (element dependent) • Requires a post-accelerator

The acceleration is done using an existing cyclotron, CYCLONE. Unfortunately, the unstable ions are injected together with intense (several orders of magnitude larger) beams of stable elements having almost the same mass over charge ratio (m/q). To achieve a high purity in the final beam, the cyclotron is tuned as a radio-frequency mass spectrometer, so that the intensity of isobaric contaminants is considerably reduced after the acceleration process. In an isochronous field the mass resolving power R= (q/m)/Δ(q/m) is given by: $R=2\pi$ h N / sin ϕ_0, where h is the harmonic number, N is the number of turns required to the full energy, and ϕ_0 the initial phase. In order to reach the high mass resolving power the number the number of turns has to be large, which implies a low dee voltage. This has the effect to reduce considerably the acceleration efficiency.

3.1.1 Future upgrade

A new cyclotron is presently under construction, CYCLONE44. It will cover the energy range between 0.2 and 0.8 A*MeV, and it is designed to combine the high acceleration efficiency (one order of magnitude larger than it is in CYCLONE), with a high mass resolving power, in order to provide pure radioactive beams of low intensity in the presence of intense isobaric contaminants. The main challenge in the design of CYCLONE44 lies in the combination of these two requirements. The resolving power is proportional to the number of turns times the harmonic number, thus requiring low dee voltage and high harmonic modes. On the other hand, a large acceleration efficiency can only be obtained if the axially injected low energy beam is perfectly matched to the cyclotron central region acceptance in the six dimensional phase space. This requirement calls for a low harmonic number, high injection voltage and high dee voltage.

3.2 The Holifield Radioactive Ion Beam Facility

The Holifield Radioactive Ion Beam Facility HRIBF has the mission to provide an economic first generation RIB facility [8]. The HRIBF utilizes two existing accelerators, the Oak Ridge Isochronous Cyclotron (ORIC) and the 25 MV tandem. In the past ORIC served as an energy booster for stable heavy ion beams from the tandem. For RIB production this process has been reversed: ORIC will produce the RIB that will be accelerated using the tandem.

The ORIC accelerator is used to bombard a thick target. High intensity light-ion beams such as 50 µA of 100 MeV alphas, 50 MeV deuterons, or 60 MeV protons are transported to the RIB injector to bombard a thick target material. The injector is located in a heavily shielded room which was originally designed to house the experiments utilizing the 1 mA 75 MeV proton beams. The ion source platform houses the target/ion source assembly, the first mass separator stage and a cesium charge exchange cell for conversion of positive ions to negative beam.

The use of the existing 25 MV tandem accelerator was clearly dictated by its availability. Tandem accelerators possess some attributes which make them attractive for this type of application. They have a large phase acceptance, and have the ability to accelerate singly charged particles with low initial velocity. The main disadvantage is the fact that tandem require a negative ion beam. In some cases it is not possible to create negative ions with high efficiency.

3.2.1 Future upgrade of the HRIBF

This first generation RIB accelerator has several limitations; the limited energy provided by the tandem and the limitation in energy of the production accelerator. The low energy of the primary beam limits the intensity of RIB far from the stability. HRIBF has several possibilities for upgrade; 1) they can add a superconducting booster in order to reach the coulomb barrier for heavier masses, 2) replacing ORIC by a modern cyclotron to provide higher primary beam energy and higher intensity.

3.3 The RNB facility at KEK Tanashi (INS Tokyo)

At INS, University of Tokyo, an ISOL based RIB facility in now in operation after 4 years of construction [9]. The INS RIB facility is a prototype for the Exotic Nuclear Beam Arena (E-Arena) of the Japanese Hadron Project (JHP). It was built in order to develop critical techniques such as a highly efficient ion source, a high resolution isotope separator, a versatile RIB accelerator.

The radioactive nuclides are produced in a thick target using a 2 µA proton beam coming from a K=67 SF cyclotron. Three different types of ion sources have been developed to ionize the various elements: surface ionization, Forced Electron Beam Induced Arc Discharge (FEBIAD) and an ECR ion source.

The separated beam with a charge to mass ratio greater than 1/30 is injected at 2 A*keV into a Split Coaxial RFQ (SCRFQ) linac operating at 25.5 MHz. After stripping at 170 A*keV the beam is injected into an Interdigital H type RF structure composed of 4 cavities operating at twice the RFQ frequency (51 MHz) accelerating ions with a mass to charge ratio 1/10. The output energy is variable from 0.170 to 1.05 A*MeV.

3.3.1 Future RIB, JHP (E-Arena)

INS and KEK, the National Laboratory for High Energy Physics, have merged as a new organization as of April 1997. The new National Laboratory aims at promoting the JHP. In the E-Arena, it is planned to use a 10 µA proton beam from the 3 GeV rapid synchrotron booster for the production of exotic nuclei.

3.4 SPIRAL project at GANIL

GANIL is a well-known heavy ion facility based at Caen (France) operating since 1983. It is composed of a cascade of three cyclotrons; C01,2, SSC1 and SSC2. The two SSC produce beams up to 95 A*MeV for fully stripped ions. This facility has been producing RIB with the projectile fragmentation method using the recoil spectrometer LISE [10] and SISSI [11]. Some years ago, the beam intensity was upgraded up to $2x10^{13}$ pps for light ions up to Ar. As an extension to the existing RIB facility, GANIL has been funded in December 1993 to develop an ISOL based facility, SPIRAL, using a new K=262 MeV SSC [12].

The primary beam accelerated by the GANIL cyclotrons will bombard a production target located inside a well-shielded cave beneath ground level in the existing machine building. It was shown [13] that using heavy ions as the primary beam can be competitive in some area to the so called classic ISOL where high energy protons are used to bombard a heavy element target. In the case of heavy ions the projectile fragmentation is the process of most importance. In all cases, the reaction products are stopped in the target. The originality of the SPIRAL project lies in the use of an extended range of heavy-ions, up to the maximum available energies of 95 A*MeV for 36 Ar. The chosen target is made from carbon and it is designed in such a way that it can stand very high power density of the Bragg peak.

The new cyclotron under construction (CIME) is a room temperature compact cyclotron of K=265 MeV with an average magnetic field between 0.75 and 1.56 T and an ejection radius of 1.5 m. The energy range is 1.7 to 25 A*MeV. The resonators should be ready in May this year. Then injection is done using a 34 mm radius Mueller type inflector for harmonic 2,3 and 4. For harmonic 5 a new inflector with a radius of 45 mm is under investigation. The extraction is done using two electrostatic and two magnetic channels. One other aspect of the SPIRAL project is the use of a cyclotron like Louvain-la-neuve as a mass spectrometer.

The first proposed beams for SPIRAL will be limited to noble gases elements $^{6,8}He$, $^{17,19}Ne$, $^{23,27}Ne$, $^{32,35}Ar$, $^{41,46}Ar$ and $^{72,77}Kr$. The projected intensities range from $5x10^3$ for ^{17}Ne to $6x10^8$ for ^6He.

The first stable beams will be accelerated at the end of 1997, while commissioning of the target and ion source assembly will begin in early 1998.

3.5 REX-ISOLDE RIB facility

A pilot experiment is proposed to study very neutron rich isotopes in the region around the neutron shell closure of N=20 and N=28 after Coulomb excitation and neutron transfer [14]. To do this the plan is to accelerate the ISOLDE beams up to 2 A*MeV by the means of a new linear accelerator. The linear accelerator concept will require the development of a charge state booster capable of producing ions with a charge to mass ratio greater the 1/4.5.

ISOLDE uses the 1 GeV proton beam from the CERN PS booster delivering a 2 µA time averaged proton beam with a pulse at 0.4 to 0.8 Hz rate. This facility is operating since more than 25 years producing a very wide range of isotopes for applied and fundamental sciences research.

REX-ISOLDE is considered like other experimental equipment. The ISOLDE 1+ beam will be injected into a Penning ion trap which will be used as an accumulator and buncher device to convert the DC beam into 50 Hz pulses. These pulses will then be injected into a charge state booster consisting of an Electron Beam Ion Source (EBIS). The pulsed beam will be injected into a 4-rod RFQ that will bring the ions energy from 10 to 500 A*keV, an 11-gap Interdigital H type RF structure then increases the energy to 1.0 A*MeV, and finally three 7-gap resonators accelerate the beam to 2.0 A*MeV. All the linac accelerating structures operate at 108 MHz and the system is pulsed at 50 Hz with a 5% duty cycle.

3.6 EXCYT project, LNS Catania

The Laboratorio Nazionale del Sud is equipped with a 15 MV tandem and now with a K=800 MeV superconducting cyclotron [15]. These accelerators will be reconfigured in order to provide an ISOL type RIB facility.

In order to increase the energy and the intensity from the SC cyclotron, a new 14.5 GHz, 1.4 T, superconducting ECR ion source was constructed for axial injection. The aim is to extract from the SC cyclotron beam currents of the order of 1 µAp. This is a challenge for this type of cyclotron, and the electrostatic deflector will have to stand very high power of the order of 3 kW coming from the extracted beam.

The negative ions will be produced with a new 150 kV injector, similar to the HRIBF concept and injected into the 15 MV tandem accelerator. RIB up to mass 40 will be accelerated above the Coulomb barrier. The EXCYT project has been funded in 1995 and the commissioning of the facility will start in the middle of 1998 and operation in 1999.

3.7 ISAC RIB facility at TRIUMF

In June 1995 the ISAC project was funded to build a RIB facility based on the 500 MeV and 100 µA H- cyclotron [16]. A new beam line is under construction which will guide the beam from the cyclotron vault through the wall into a new tunnel extension. Then beam can be sent to two target stations located into a heavily shielded area. A new building of approximately 5000 m^2 is under construction. This building is divided into two parts, the target handling hall and the accelerator/experimental area hall. The remote handling target concept is based on twenty years of experience in meson production targets. Each target station comprises five modules, primary beam entrance, target/ion source, beam dump and two exit modules containing the front end of the mass separator. All the components are attached at the bottom of a 2 m long steel plug. The target stations are housed in a canyon heavily shielded for a primary proton beam intensity up to 100 µA.

The ion beam from the mass separator can be sent either to the Low Energy Experimental area or to the linear accelerator. The ions with a charge to mass ratio greater than 1/30 are accelerated from 2 A*keV to 150 A*keV by a 4-rod split-ring RFQ operating at 35 MHz in CW mode. After stripping and charge analysis the beam is injected into a Drift-tube linac. The output energy is fully variable from 0.15 to 1.5 A*MeV, using a separated function Drift-Tube-Linac.

A prototype of the split-ring 4-rod RFQ composed of three modules has been tested at full CW power (85 kV inter-electrode voltage) [17].

For the DTL, a new approach was taken in order to deliver a fully variable output energy. Five independently phased IH tanks operating at $\Phi_s = 0°$ provide the main acceleration. Longitudinal focusing is provided by three independently phased 3-gap resonators positioned before the second, third and fourth IH tank. They permit the beam to be kept well bunched over the entire energy range [18].

The first phase (Low Energy Experiments) will be operational by the end of 1998, and the accelerated RIB will become operational a year later.

4 UPGRADE OF PROJECTILE FRAGMENTATION FACILITIES

4.1 Upgrade of the NSCL at Michigan state university

The NSCL has developed a plan to upgrade and couple its existing Superconducting Cyclotron K500 and K1200. Also they propose to replace the present A1200 beam analysis system by an improved A1900 beam analysis system [19]. The upgrade will greatly enhance the performance of the NSCL facility, particularly for studies using radioactive ion beams. The K500 will be disassembled and rotated by 120 degrees from its present orientation. Its central region will be redesigned to allow a more efficient acceleration in the second harmonic mode and to increase the turn separation. A new beam line will be constructed for the coupling between the K500 and K1200 cyclotrons. The beam is then injected radially. After stripping to a higher charge state, the beam will be accelerated to full energy. The improvement in intensity is a result of the lower charge states required from the ECR ion source for the K500⊗K1200 mode. The improvement in energy for mid and high mass nuclei comes from the higher charge state obtained after stripping into the K1200. For example, the maximum energy for 238U will be 110 A*MeV instead of 25 A*MeV in the present configuration. The overall result for RIB production is an increase by a factor 10^3 to $4x10^4$ for ^{11}Li to ^{132}Sn.

4.2 RIKEN upgrade

RIKEN, Accelerator Research Facility (RARF) proposes an upgrade consisting in an intensity upgrade by replacing the high voltage platform by a combination ECR ion source and a 4-rod folded coaxial variable frequency RFQ. In Addition to the existing K540-MeV ring cyclotron (RRC) two new cyclotrons will be built [20]. A K930-MeV room-temperature ring cyclotron (RC4) and a K2500-MeV superconducting ring cyclotron consisting of six sectors (SRC6). The maximum beam energy of the RC4 is 135 A*MeV and 400 A*MeV for SRC6.

The project was formally approved in December 1996 and the design is nearly completed. The commissioning is due for the year 2002. With the combination of new high intensity injector and post-accelerator delivering heavy ion of several hundreds of A*MeV RIKEN will become the most intense source of RIB using the in flight separation technique.

4.3 SIS/GSI (Darmstadt, Germany) upgrade

GSI possesses one of the most powerful projectile fragmentation facilities. SIS can accelerate heavy ions up to 2 A*GeV. Combined with the Fragment Recoil Separator (FRS) a very wide range of radioactive ion beams can be produced. The limiting factor at the moment is the primary beam intensity.

At present SIS uses the original UNILAC as injector, not designed originally to be a dedicated synchrotron injector.

In order to fill the SIS up to its inherent intensity limit the linac has to be modified [21]. The limit is set by the space charge effects at the injection. Improvement on ion source are required.

The choice of $A/q \leq 65$ for the new linac design is in accordance with the "state of the art" for the ion source. For the new pre-stripper linac, a frequency of 36 MHz is chosen, which is one third of the Alvarez frequency.

A novel approach for the RFQ structure is used. The RF mode is the H_{110}- mode which is similar to the one used in Interdigital H type RF structure. The RFQ tank is 1 m in diameter and 9.4 m long. The IH-DTL is composed of two cavities, 9.15 and 10.2 m long. The first tank contains 3 quadrupole triplets and the second only one. Triplets are used for the transverse focusing. Quadrupole magnets are laminated, and the field at the surface of the pole is 1.35 T. With this intensity upgrade SIS will be able to run at the space charge limit in 1998.

5 PROPOSED RIB BASED ON ISOL METHOD

5.1 Argonne National Laboratory

The Argonne concept for a RIB facility is based on the use of the existing superconducting linac as the major part of the post-accelerator. The new components for the RIB facility will be constructed in a new building north of the existing ATLAS facility. The driver accelerator can be a conventional 215 MV linear accelerator or a superconducting linac using a two-gap superconducting niobium resonator.

Acceleration of low q/m RIB will requires a sequence of three new subsystems; a short low frequency RFQ and two sections of superconducting linac optimized for these low charge state ions. After acceleration at energies between 0.5 and 1. A*MeV the secondary beams can be delivered to the new experimental area. For further acceleration the beam will be injected into the actual ATLAS facility.

Prototyping of the 12 MHz split-coaxial RFQ have started, and they plan having a 40 kW RF amplifier running by the end of the summer, and test in the fall, [22].

5.2 PIAFE

The project PIAFE in Grenoble plans to take advantage of the proximity of the high neutron flux (10^{14} n/s/cm^2) from the Institut Laue-Langevin nuclear reactor (ILL). The radioactive ions will be produced via induced fission of ^{235}U by thermal neutrons [23]. After two successive mass-analysis, inside the ILL reactor building, the beam will be sent to a high mass resolution separator, first phase (PIAFE1). In the second phase (PIAFE2), the singly charged ions will be guided to the SARA accelerator complex of the Institut des sciences nucléaires (ISN-Grenoble). Before being injected into the cyclotron the singly charged ions will be converted into higher state using an ECR as charge state breeder. The final energy will be comprised between 2 and 10 A*MeV.

5.3 Beijing Radioactive Nuclear Beam Facility (BRNBF)

The Beijing Radioactive Nuclear Beam Facility proposed and ISOL type RIB facility based on a high intensity proton beam produced by a 70 MeV H$^-$ cyclotron. After mass analysis the RIB will be accelerated using an existing HI-13 tandem accelerator [24].

6 DISCUSSION

The use of intense RIB opens new possibilities and it is a very active field. The demand for high energy RIB beam around the Coulomb barrier is very challenging for accelerator physicists.

The choice of the post accelerator depends on the physics program, which defines the energy and mass range requirements. First generation RIB facilities take advantage of existing accelerators;

- Louvain-la-neuve, cyclotron
- HRIBF, tandem
- EXCYT, tandem

Table 2 shows a list of the advantages and disadvantages of different types of accelerator used or proposed for post-acceleration of RIB.

Together, these RIB facilities will cover a very large energy range, from the low energy required for nuclear astrophysics to the Coulomb barrier, intermediate energies and above the Fermi energy. A new field of experiments will be possible and will give us insight into the nucleosynthesis in stars, novae and supernovae, nuclear structure, and investigation of exotic nuclear matter.

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Table 2. Comparison between different post-accelerator

Accelerator	Advantages	•Disadvantages
Tandem	• Can accelerate singly charge ion • Reliable operation, • Energy continuously variable • Good beam quality.	•Require negative ion •Require high voltage injector, not compatible with high radiation field around the target •Require high voltage; V> 25 MV to reach the Coulomb barrier
Cyclotron	• Can obtain high energy at low cost: E ≤ A•20 MeV • Can be use as a mass spectrometer	•Required high charge state; expertise on on-line ion source for singly charged ions only. •Very large contamination of the central region. •Large energy spread
LINAC	• Good transverse and longitudinal emittance • Energy fully variable • Good transmission	•Require low frequency RFQ •CW mode required efficient rf structures