WORLD-WIDE EFFORTS ON RARE ISOTOPE AND RADIOACTIVE ION BEAMS

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Abstract

An overview of the increasing activities of rare isotope and radioactive ion (RI) beam accelerator facilities worldwide is given. Starting with the production methods for RI beams, the present status of and developments at recently commissioned RI beam facilities are reviewed. The complimentary nature of the facilities as well as key technologies are highlighted.

INTRODUCTION

The advent of rare isotope and radioactive ion (RI) beam accelerator facilities in the late 1980s provided a means to access the unexplored region on the nuclear chart, far from the stability line. Since then, unexpected characteristics have been revealed in unstable nuclei, such as the presence of dilute neutron distribution around the core, an unusual shell structure, and new excitation modes, which have motivated us to find a new comprehensive way to describe atomic nuclei. Moreover, detailed studies on unstable nuclei are expected to improve our understanding of how heavy elements were formed in the universe through the so-called r-process during stellar explosions.

It should be emphasized that to study the different regions of the nuclear chart, a wide variety of RI beams are required; the ion species, intensity, and quality of the beam required strongly depend on the scientific objective. In fact, the discoveries mentioned above were not made at a single facility, but at a number of facilities that are complementary [1, 2]. Another important point is that a wide variety of technologies are required for constructing RI beam facilities, as discussed in the next section. Therefore, well-organized collaborations among the facilities are important to study a wide range of R&D subjects.

This paper reviews the increasing activities of the RI beam facilities in the world. In the next section, production methods for RI beams are briefly discussed, and important components of the facilities are highlighted. The complementary nature of the RI-beam facilities is clearly stated. In the third section, the present status of and developments at some of the RI beam facilities are outlined, focusing on those recently started, those under construction, those being upgraded, and those being planned.

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RI BEAM PRODUCTION

There are two traditional ways of producing RI beams. The first one is the so-called "in-flight method" as shown in Fig. 1, where radioactive ions are obtained through fragmentation or fission reactions induced by energetic heavy ions colliding with a thin target made of light elements such as carbon and beryllium. The reaction fragments, ejected in the forward direction with almost the same speed as that of the incident beam, are separated with an in-flight fragment separator and transferred to the experimental apparatus as the RI beam. The advantage of this method is that

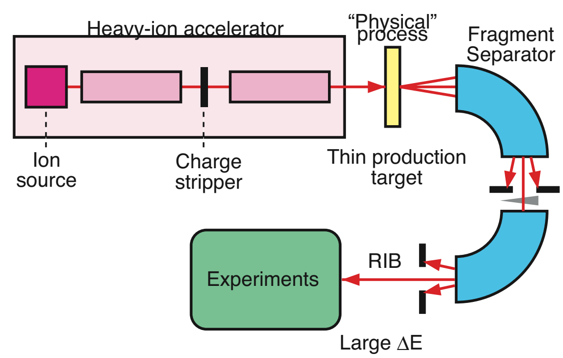

Figure 1: Schematic drawing of the in-flight production method.

the production of RI beams is independent of the chemical properties of the element. Moreover, isotopes with very short half-lives and even isomers are available as RI beams. On the other hand, the quality of the RI beams is poor due to the kinematic energy spread and their divergence that results from the production process.

From a technological viewpoint, the most important component is the high-intensity accelerator of heavy ions. A beam energy larger than 100 MeV/u ($\beta \geq 0.4$) is required. On the other hand, the production targets are essential as well for effective RI-beam production. The charge strippers are also crucial for high-power heavy-ion beams.

The second method is the ISotope On-Line (ISOL) scheme shown in Fig. 2. This method is based on light-ion induced spallation or fission of thick targets made of heavy elements such as tantalum or uranium (uranium carbide), where intense protons and deuterons of 20-1000 MeV/u are used as the driving beams. The radioactive fragments diffuse out of the target and effuse to an ion source to become singly charged ions. After passing through a high-resolution magnetic separator, the charge state is boosted by a charge breeder to achieve a high acceleration efficiency in the post-accelerator. The advantage of

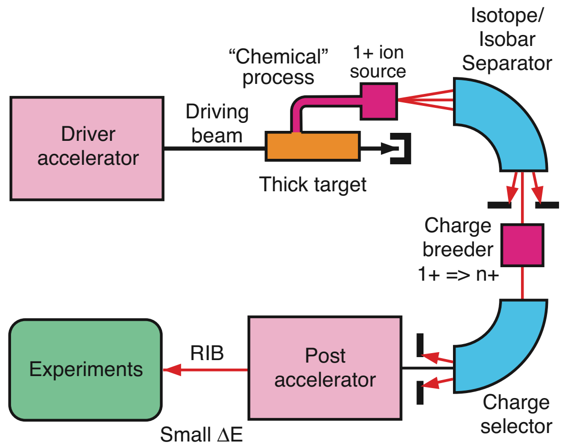

Figure 2: Schematic drawing of the ISOL production method.

this method is that the quality of the reaccelerated beam is excellent and suitable for detailed studies of nuclear reactions and structures. It is also useful for stopped-beam experiments such as the experiments involving the use of ion traps and laser spectroscopy. On the other hand, the production process strongly depends on the chemical properties of the produced isotopes, and it is generally difficult to provide chemically active elements as RI beams. Short-lived isotopes cannot be obtained because of the time required for diffusion and effusion. In this sense, the ISOL method is complementary to the in-flight method.

The most crucial component in this method is the driver accelerator that is capable of providing high-power beams. For high-efficiency production of RI beams, however, the R&D of the targets, ion sources, and charge-breeders are essential as well.

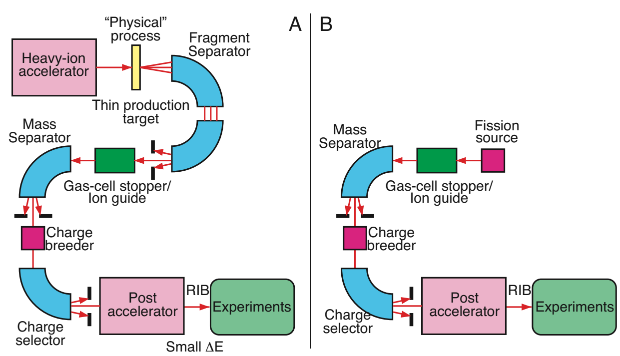

Figure 3: Catcher-reacceleration scheme (A) and direct scheme starting with fission source (B).

Recent improvements to the gas catcher system have made it possible to obtain low-energy RI beams at in-flight facilities, as shown in Fig. 3A. The beam quality is excellent in this scheme, while the production process is independent of the chemical properties of the produced elements, i.e., the advantages of the in-flight and ISOL methods are integrated. Another variation based on the catcher system is shown in Fig. 3B; here, the fission products are directly used and the production of RI beams with the heavy-ion accelerator is not required. The gas catcher and charge breeder play significant roles in these techniques.

FACILITIES IN THE WORLD

In this section, recent activities of RI beam facilities are outlined in three subsections that are categorized on the basis of the production methods: in-flight, catcher-reaccelerator, and ISOL facilities.

In-flight Facilities

RIKEN RIBF [3] The RIKEN RI Beam Factory (RIBF), which started in 2006, has two injectors (the heavy ion linac and AVF cyclotron) and four booster cyclotrons (RRC, fRC, IRC, and SRC). Combining these accelerators in a cascade, all types of ions from protons to uranium ions can be accelerated up to 70% of the light speed in the cw mode. The accelerated beams are transferred to BigRIPS, where the RI beams are generated. The Zero-Degree and SHARAQ spectrometers have already been constructed, and the SAMURAI spectrometer is under construction. The cw-mode beams are suitable for spectrometer experiments.

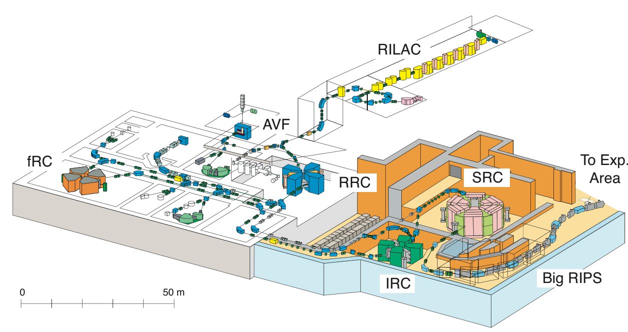

Figure 4: Layout of the accelerator complex of RIKEN RIBF.

The main accelerator of the RIBF is the superconducting ring cyclotron SRC [4]. The SRC, consisting of six sector magnets, is the first superconducting ring cyclotron in the world, and it has the maximum K-value, 2600 MeV. The beam intensities achieved so far are 1000 pnA for alpha particles, 170 pnA for ^{48}Ca, and 0.8 pnA for ^{238}U [5].

Nuclear physics experiments involving the use of the RI beams commenced three years ago, and remarkable results have been obtained. For example, 45 new isotopes were found in a short experiment in the fission products of a uranium beam by using the BigRIPS spectrometer [6], including several isotopes on the reaction path of the r-process.

GSI and FAIR [7] The GSI facility is recognized for outstanding achievements in the field of rare isotope science. Among them, the Schottky and TOF methods that involve the FRS spectrometer and cooler-storage ring ESR

Table 1: RI-beam Facilities recently commissioned, those under construction, and those being planned

In-flight facilities	**Driver**	**Mass**	**MeV/u**	**I (pps)**	**Separator**	**Exp.**
RIBF (RIKEN, Japan/2006)	SRC	1-238	440-345	6×10^{12}	BigRIPS	ZDS etc.
HIRFL (IMP, China/2006)	CSRm	1-238	2800-500	10^{9}	RIBLL2	CSRe
FAIR (2013)	SIS100	1-238	30000-2700	10^{12}	SuperFRS	CR etc.
FRIB (USA/2017)	Sc. linac	1-238	610-210	5×10^{13}	A1900	ReA12
Catcher-reacc. facilities	**Driver**	**Mass**	**MeV/u**	**Breeder**	**Post acc.**	**MeV/u**
ReA3 (MSU, USA/2010)	K1200	1-238	170-80	EBIT	Sc. linac	3-6
CARIBU (ANL, USA/2010)	(^{252}Cf)	-	-	ECR	ATLAS	15
ISOL facilities	**Driver**	**Mass**	**MeV/u**	**kW**	**Post acc.**	**MeV/u**
ISAC-II (TRIUMF, Canada/ 2015)	Cyclotron e-linac (sc.)	1 (e)	500 (50 MeV)	50 500	Sc. linac	18
RIB (VECC, India/2012)	Cyclotron	4	16	1.2	Linac	1.3
Spiral2 (GANIL, France/2012)	Sc. linac	2	20	200	CIME	2-25
HIE-ISOLDE (CERN/2015)	PS	1	1400	10	REX upgrade	3-10
SPES (INFN, Italy/2012)	Cyclotron	1	50	8	ALPI	10
EURISOL (2025)	Sc. linac	1	1000	4000	Sc. linac	150

have been developed; the methods have led to the observation of new mass values for 350 isotopes and have led to the determination of accurate mass values for 300 isotopes.

The international project FAIR, which is expected to start in 2013, is the expansion of the projects of the present GSI facility. The available beam energy will be increased by twenty times by installing the synchrotrons SIS100/300. Along with the upgraded performance of the superconducting fragment separator (Super-FRS), the secondary beam intensity will be improved by a factor of ten thousand. One of the four major programs of FAIR is the NUSTAR collaboration, which aims to carry out studies on rare isotope nuclear physics using the Super-FRS facility. This project will expand our existing knowledge of the nuclear physics significantly through the use of the new storage rings, both in the high- and low-energy regions.

IMP HIRFL [8] The Institute of Modern Physics in Lanzhou started the operation of a new facility in 2006; this facility comprises two cooler storage rings (CSRm and CSRe) and a fragment separator, RIBLL2. Heavy-ion beams are injected by the coupled cyclotron system. Recently, by using the CSRe in the isochronous mode, researchers measured the masses of several nuclei around the proton drip line with excellent accuracies. They also have a medium-range plan to construct a new linac injector to increase the primary beam intensity in the storage rings.

FRIB [9] The United States DOE project FRIB is under progress at the Michigan State University, and it is expected to start operation in 2017. The driver beam includes a 400 kW uranium beam of 200 MeV/u that is accelerated by a long superconducting linac and is based on the innovative concept of multi-charge acceleration [10].

This project has a baseline option to reaccelerate RI beams through a gas catcher. The final energy of the reaccelerated beam is 12 MeV/u for nuclei ranging over the complete mass range of the nuclear chart.

Catcher-reaccelerator Facilities

ReA3 [11] at NSCL, MSU The construction of the reaccelerator part of the FRIB program has already started as the ReA3 project of MSU, and heavy-ion beams provided by the NSCL coupled superconducting cyclotrons will be used.

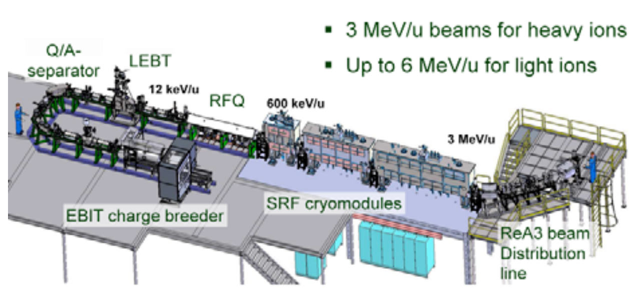

Figure 5: ReA3 facility at NSCL, MSU.

The ReA3 accelerator system is shown in Fig. 5. The singly charged ions from the gas stopper are guided to the ReA3 platform by a beam line using electrostatic elements, and they are then injected into the EBIT charge breeder. This charge breeder is essential for effective acceleration with the compact linac structure, which consists of a 4-rod RFQ and superconducting linacs. The ReA3 system is expected to become operational this year, and the energy upgrade program, ReA12, is planned before the FRIB driver linac is commissioned.

CARIBU at ATLAS, ANL [12] In parallel with the upgrade plan of the ATLAS superconducting linac, a new pre-injector section has been constructed for the reacceleration of neutron-rich beams from a ^{252}Cf fission source; the construction is part of the CARIBU project. Since the distribution of the fission products of californium is different from that of uranium, this facility is complementary to the in-flight facilities using uranium beams such as RIKEN, GSI, and FRIB.

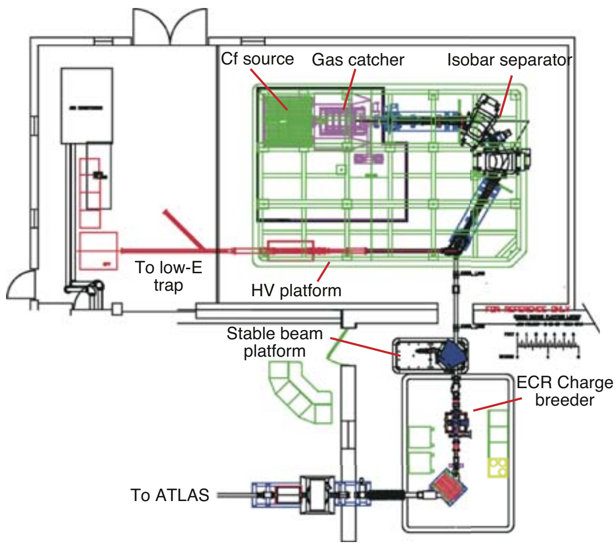

Figure 6: Floor plan of CARIBU project at the ATLAS facility, ANL.

The starting point is the ^{252}Cf source of 1 Ci in a shield cask together with an effective gas catcher on a high-voltage platform, as shown in Fig. 6. The singly charged ions from the gas catcher pass through the high-resolution isobar separator, and their charge state is then boosted by the ECR charge breeder. Finally, they are accelerated by the ATLAS linac up to 15 MeV/u. The construction of the pre-injector section has been completed and it has been commissioned with a weak source.

ISOL Facilities

ISAC at TRIUMF [13] Since the 1990s, the ISOL-based facility ISAC has been developed at TRIUMF and now the superconducting linac is providing RI beams such as ^{11}Li beams with remarkable intensities. The driver beam currently used is 50 kW protons provided by the 500 MeV TRIUMF cyclotron.

TRIUMF has recently proposed a five-year plan [14], whose implementation is expected to start this year. It includes an upgrade program for increasing the production of radioactive isotopes, not only for physics research but also for medical applications, by installing new target stations and an electron linac driver capable of providing 500 kW beams. The superconducting rf system is one of the key technologies driving the future plans.

VECC [15] The Variable Energy Cyclotron Center in Kolkata is constructing an RI-beam facility, which is based on a cyclotron driver. They are constructing a normal conducting linac as the post-accelerator, and recently started a development program that involves the construction of a superconducting electron linac for use as a new driver. The first phase of the program that involves the cryomodule of a 10 MeV injector is being implemented in collaboration with TRIUMF.

Spiral2 at GANIL [16] In addition to the in-flight facility LISE, GANIL has been operating the ISOL facility Spiral since 2001, where the driver beam is provided by the coupled cyclotron system. Spiral2 is a plan to increase intensity of the driver beam by constructing a powerful linac as shown in Fig. 7. The 20 MeV/u, 200 kW deuteron beam will be converted into a neutron flux by a carbon converter so that the uranium carbide target could have a designed fission rate of 10^{14}/s.

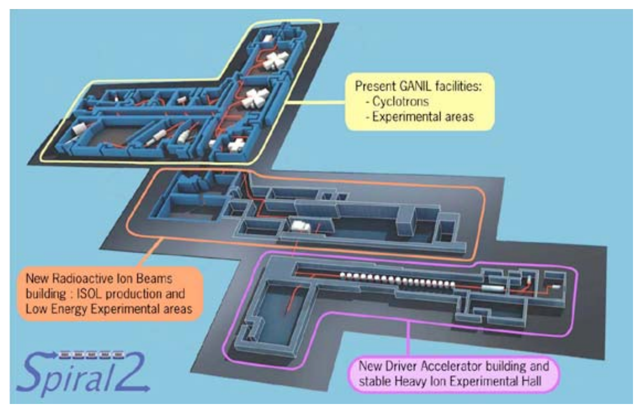

Figure 7: New and existing facilities at the GANIL site.

The baseline configuration of the driver linac uses quarter-wavelength superconducting cavities of 88 MHz. The construction of the cavities is under progress at Saclay for the low-energy part ($\beta = 0.07$) [17] and at Orsay for the high-energy part ($\beta = 0.12$) [18]. The linac is designed to accelerate not only deuterons but also heavy ions (m/q < 6) for stable-beam experiments. The linac is expected to be commissioned in 2012.

HIE-ISOLDE at CERN [19] Development of the SRF technology is being carried out at CERN-ISOLDE, which is one of the facilities pioneering studies in rare isotope science. The present reaccelerator REX provides RI beams with a maximum energy of 3 MeV/u; the reaccelerator consists of an ion trap, EBIS breeder, and normal conducting linac.

There is a three-stage upgrade plan to increase the RI-beam energies up to 10 MeV/u by introducing a superconducting linac booster. The cavities are based on the Nb sputtered structure of 101 MHz, and they will be mounted in the cryomodule that was designed carefully by taking the maintenance service at CERN into account. The upgrade plan will be implemented over the next five years.

SPES [20] The production target system is one of the most crucial components in ISOL facilities. The SPES project, to be built at INFN-Legnaro, is an ISOL facility based on a cyclotron driver, where the superconducting linac, ALPI, will be used for the reacceleration of RI beams. This project is characterized by R&D activities pertaining to a uranium-carbide target and is a collaboration among the INFN laboratories and Italian universities [21].

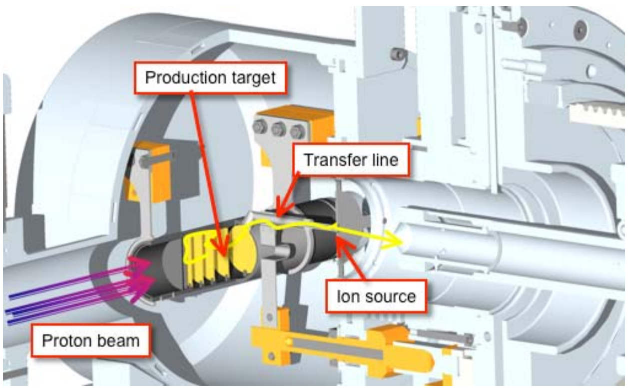

Figure 8: Schematic drawing of the target developed for the SPES project.

Figure 8 shows a schematic drawing of the target system, including uranium carbide multi-foil on which protons with a power of 8 kW will impinge. The configuration is carefully designed to keep the fission rate as high as 10^{13}/s with moderate heat deposition, as well as to release the produced ions in a short time. A prototype of the target system has been manufactured at Legnaro and various tests are under progress. For example, the fabrication process of the foils and the thermal behavior of the target are being investigated.

EURISOL [22] The design study of the EURISOL project has been managed by a large consortium of European institutes. According to the design report that was published recently, the baseline design considers the acceleration of a 4 MW beam of protons by a superconducting linac to achieve a uranium fission rate of 10^{15}/s; a mercury converter is also used. The post-accelerator will also be constructed using SRF technologies. The final energy has been chosen to make secondary fragmentation possible with the reaccelerated RI beams in order to reach close to the neutron drip line. The expertise of Spiral2, ISOLDE, and SPES projects will be integrated in this ambitious project, which is expected to start about fifteen years later.

SUMMARY

A summary of the facilities discussed in this paper is given in Table 1.

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