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World new facilities for radioactive isotope beams

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Abstract. The use of unstable nuclei in the form of energetic beams for nuclear physics studies is now entering into a new era. “New-generation” facilities are either in operation, under construction or being planned. They are designed to provide radioactive isotope (RI) beams with very high intensities over a wide range of nuclides. These facilities are expected to provide opportunities to study nuclear structure, astrophysical nuclear processes and nuclear matter with large proton-neutron imbalance in grate detail. This article reports on the current status of such new-generation RI-beam facilities around the world.

1 RI beams in nuclear physics studies

1.1 Extension of our knowledge in the nuclear chart

Radioactive isotopes (RI), or unstable nuclei, play a crucial role in enhancing our knowledge on atomic nuclei. The discovery of new methods for artificial RI production has advanced nuclear physics research substantially. A total of around 500 isotopes were known in 1940, including almost 300 stable ones. The number of known nuclides has increased in a linear manner since then, with some variations due to social constraints or technical innovations [1]. The nuclear chart, shown in Fig. 1, exhibits the present status of our knowledge. About 3,000 isotopes including 2,700 radioactive ones have been identified so far. According to theoretical predictions by, for example, the KTUY theory [2], another 7,000 isotopes might exist if fissioning nuclei with lifetimes longer than 1 μs are counted as well as β emitters [3]. The effort to extend our knowledge on the nuclear chart is an ongoing process: construction of new facilities and development of new experimental methods should support such activities.

1.2 Development of RI beams

In the mid 80s, the idea of using unstable nuclei in the form of energetic beams was realized for the first time at LBL [4]. The projectile-fragmentation reaction with fast ion-beams was the mechanism to produce RI’s in-flight. The first application of these RI beams was to measure interaction cross sections of light unstable nuclei. The enhancement of matter radius owing to neutron halos was observed for some light, neutron-rich nuclei. This success triggered the construction of new facilities that could provide RI beams with high intensities using the same production method. In the 90’s, dedicated

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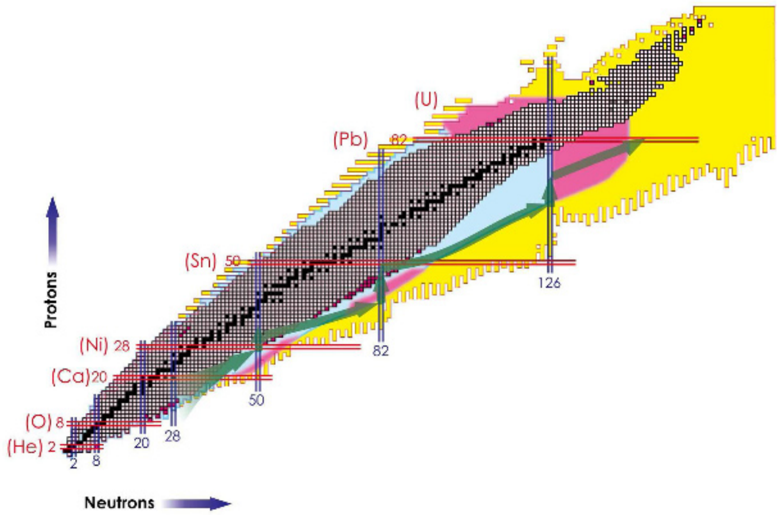

Figure 1. Nuclear chart. Stable nuclei are indicated by filled squares, and nuclei created so far by open squares. The yellow area represents nuclei that are expected to exist (see the text). The purple, red and light blue parts indicate isotopes whose production at RIKEN RIBF is expected to be higher than 1 particle per day when the primary-beam intensity exceeds a rate of 1 particleμA (using in-flight fission, fragmentation of uranium beam and fragmentation of lighter beams, respectively). Expected r-process pathways are indicated by the green arrows.

RI-beam facilities were constructed at several locations around the world including GANIL(France), RIKEN(Japan), MSU(USA), GSI(Germany), and IMP (China).

Another way to produce RI beams is based on the ISOL (isotope separator on-line) technique. Unstable nuclei are produced at rest by nuclear reactions and re-accelerated by an independent accelerator. This method was successfully applied for the first time in 1989 at the laboratory of Louvain la Neuve (Belgium). The first experiment used ^{13}N beams to study the astrophysical reaction ^{13}N(p,γ)^{14}O relevant to the hot CNO cycle, one of the explosive hydrogen-burning processes [5]. It should be noted that the same reaction was studied at RIKEN with fragmentation-based RI beams almost at the same time by a completely different method, Coulomb dissociation [6].

The results from the two experiments agree well, despite difference in their experimental methods and conditions. This first success highlights the impact of RI beams, produced by both the methods, in astrophysics study. Since then, several other ISOL-based facilities have also been constructed: Spiral (France), Alto (France), ISAC (Canada) and REX ISOLDE (Switzerland/France) are examples.

The pioneering experiments discussed above symbolise the two major aspects of research using RI beams: the exotic behavior of nuclei away from the valley of stability and violent astrophysical processes involving short-lived nuclei. As already mentioned, many facilities have been constructed and appropriate techniques have been developed to study new nuclei. Thus, new light has been shed on various nuclear problems.

2 New Generation facilities

Owing to the successes of previous and current RI-beam facilities and the expectations of future RI-beam based studies, “new generation” facilities with drastically enhanced performance in producing beams of nuclei much farther from the stability valley are being planned. In order to cover different energy domains and to meet various scientific demands, their designs are of a wide variety. For example, RIBF in Japan, FAIR in Germany and FRIB in US are based on the fragmentation scheme for beams with energies of a few hundred MeV/nucleon to GeV/nucleon, whereas Spiral2 in France, SPES in Italy, HIE-ISOLDE in Switzerland/France, and the future facility EURISOL in Europe are based on the ISOL method, and aim at providing lower-energy RI beams. There are a many other projects including upgrades of existing facilities in the three continents, America, Asia and Europe.

2.1 Fragmentation-based facilities

2.1.1 RIKEN RIBF

Among the new-generation facilities, only the RIKEN RI Beam Factory in Japan is currently in operation [7]. The layout of the facility is shown in Fig. 2. Part of the facility began routine operation in 1987. RI beams with the energy of a few tens of MeV/nucleon became available in 1990, which were the highest intensity RI beams at that time for many light exotic nuclei. Together with other facilities, a number of modern aspects of nuclear structure, such as neutron-halo and disappearance/appearance of magic numbers, were investigated. Several attempts were made to approach astrophysical nuclear processes involving short-lived nuclei that had previously been difficult to be studied in the laboratory [8],

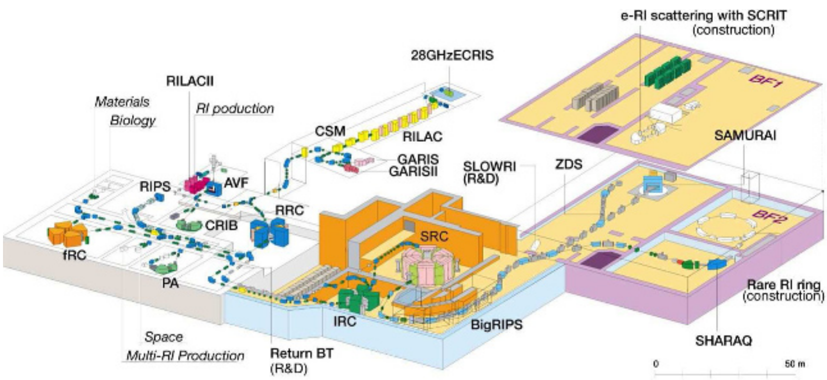

Figure 2. Schematic view of the Radioactive Ion Beam Factory (RIBF) at RIKEN. The part with gray background is the new part of the facility.

The new high-energy section of RIBF is indicated by the colored background in Fig. 2. It has three cyclotrons: fRC (fixed-frequency Ring Cyclotron), IRC (Intermediate stage Ring Cyclotron), and SRC (Superconducting Ring Cyclotron). Together with the pre-existing accelerator RRC, beams can be provided from proton up to uranium up at 345 MeV/nucleon [9]. The new fragment separator BigRIPS [10] accepts about a half of the reaction products from the in-flight fission of uranium ions, which is expected to have advantages of efficient production of neutron-rich, medium-mass nuclei, in addition to the projectile fragmentation. RI beams at around 200 MeV/nucleon were first supplied in 2007. The capability of RI beam production relative to the old part of RIBF is shown for some cases in Table 1. The primary-beam intensities are still expected to improve, and so the gain of the new facility is enormous. The ultimate goal of RIBF is to reach primary-beam intensities of 1 particleμA up to uranium. The isotopes that are expected to be created with rates higher than 1 particle per day are indicated in Fig. 1.

Table 1. Comparison of RI-beam intensities (in counts per second) at the old and new RIBF facilities.

beam	old (RIPS)	new (BigRIPS in 2009)	gain
^{22}C	6×10^{-3}	10	1,700 (3,600 in 2012)
^{30}Ne	0.2	300	1,500
^{31}Ne	6×10^{-5}	10	1.7×10^{5}
^{32}Ne		5	
^{42}Si		15 (24 in 2012)	
^{44}S		4×10^{4}	

2.1.2 FAIR AND FRIB - FACILITIES UNDER CONSTRUCTION

The Facility for Antiproton and Ion Research (FAIR) is now under construction at the site of GSI (Germany). A schematic view is shown in Fig. 3. FAIR will use the current GSI accelerators in part, much like the RIBF. With the construction of a new synchrotron called SIS100, the primary beam intensity is expected to increase by a factor of 100 to 1,000 (*e.g.* 3×10^{11} uranium at 1.5 GeV/nucleon), which should provide RI beams that are 10,000 time more intense than the current facility. In addition to Super FRS, a fragment separator, for direct use of the RI beams, a collector ring will be built to store and cool produced secondary beams, which will provide unique research opportunities similar to the ESR of the current GSI facility. RI-beam experiments are planned to start partially in 2018. In addition to RI-beam production, FAIR provides various research opportunities with anti protons and stable ions from protons to uranium. This large-scale project will be conducted by the "modularized start" scenario, where, for example, RI-beam production will be made first, and the storage rings will be constructed later.

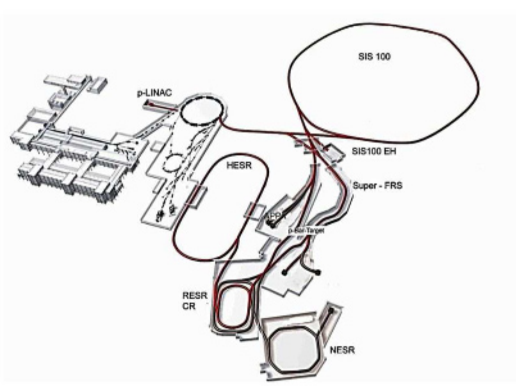

Figure 3. Facility for Antiproton and Ion Research (FAIR) being constructed in the GSI site in Germany

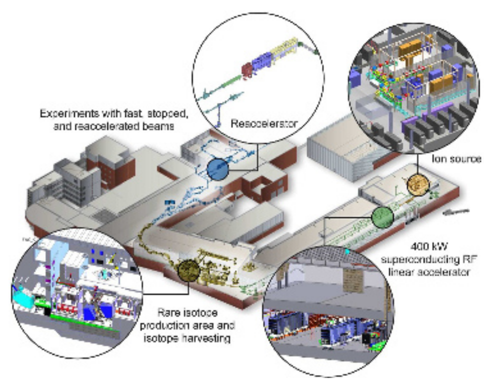

Figure 4. Facility for Rare Isotope Beams (FRIB), which will be built in the MSU campus, the United States.

The US project, the Facility for Rare Isotope Beams (FRIB), has been approved and will be completed in 2020 at earliest at the site of NSCL in MSU. As shown in Fig. 4, the driver is a superconducting linear accelerator that accelerates heavy ions up to uranium to 200 MeV/nucleon. The designed beam power of 400 kW is considerably higher than for FAIR (20 kW) or RIBF (7 kW at present, 20 kW by 2015, and 80 kW further in the future), aiming at high RI-beam intensities. The fragment separator and other beam handling systems will be built by reconfiguring the current equipment. Lower-energy (<12 MeV/nucleon) RI-beams will also be created by fast-stopping techniques applied to the fast fragmentation-based beams. Introducing the ISOL technique for low-energy RI-beams and upgrading the primary-beam energy are future options.

2.1.3 HIAF and RAON - FACILITIES TO BE BUILT IN ASIA

In Asia, two major projects for RI beams have been launched. They are the High-Intensity Heavy Ion Accelerator Facility (HIAF) in China and RAON facility in Korea.

In Lanzhou, China, a fragmentation-based RI-Beam facility called HIRFL-CSR is in operation at the Institute of Modern Physics (IMP). Construction of a new facility called HIAF is planned as a future program. The proposed accelerator complex is shown in Fig. 5. It will use 1.2 GeV/nucleon uranium beam (20 kW) for RI production. By constructing several rings for accumulation-acceleration and collecting RI beams with cooling, electron and proton beams for colliding experiments, and electron accelerator for electron-ion collisions, various types of studies can be conducted. The project has been approved, and HIAF will be constructed throughout 2013-2019 at a site independent of the current HIRFL-CSR facility.

RAON is a new RI-beam facility, which will be built in Korea under the approved project RISP (the Rare Isotope Science Project officially launched in 2011). As shown in Fig. 6, the RAON facility will have ISOL beams as well as fragmentation-based beams. The primary beams will be obtained by a series of superconducting linear accelerators providing, for example, 200 MeV/nucleon uranium. The ISOL will primarily use 70 MeV protons form a cyclotron and later 600 MeV protons with 400 kW beam power. Post acceleration is to be performed by another superconducting linac, capable of accelerating RI beams up to 16.5 MeV/nucleon.

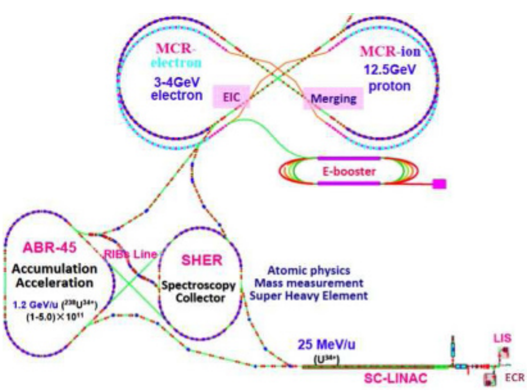

Figure 5. Schematic view of the HIAF facility planned in China.

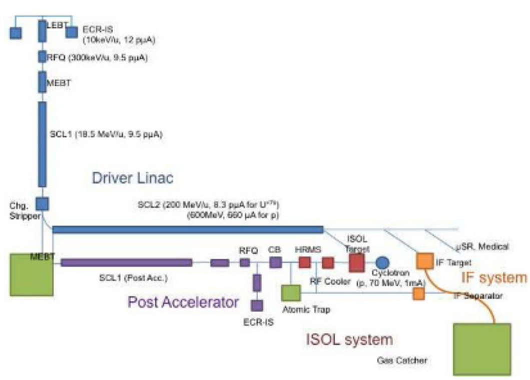

Figure 6. Korean facility RAON. Both the ISOL and fragmentation schemes are employed to produce low- and high-energy RI beams.

2.2 ISOL-based (post-acceleration) facilities

There are numerous projects planned around the globe for ISOL-based RI-beams: Spiral2 at GANIL in France, SPES at LNL in Italy, HIE-ISOLDE at CERN in Switzerland/France, ARIEL at TRIUMF in Canada, and EURISOL in Europe are examples. There are similar plans in Asia, such as Beijing ISOL in China and ANURIB in India.

2.2.1 SPIRAL2, SPES, HIE-ISOLDE, and EURISOL - EUROPEAN ISOL ROAD-MAP

Nuclear physics community in Europe defines a road-map of ISOL-based facilities through discussions in NuPECC (Nuclear Physics European Collaboration Committee). It has set a goal to construct an ultimate facility called EURISOL (European Isotope Separation On-Line Radioactive Ion Beam Facility) from 2025. 1 GeV protons with 5 MW beam power are planned to be converted to high-flux neutrons to induce 10^{15} fission/second with a uranium (UC_x) target. Before the completion of EURISOL, three projects, Spiral2, HIE-ISOLDE and SPES, are defined as "intermediate" facilities to provide opportunities to deal with many technical challenges required to realize EURISOL, as well as to conduct researches with high-intensity low-energy RI beams.

Figure 7 shows a schematic layout of Spiral2 including the current GANIL facility. The LINAC accelerates a high-intensity (5 mA) deuteron beam to 40 MeV, which induces uranium fission with a rate around $10^{14}s^{-1}$. By using the existing cyclotron CIME, RI beams of energy up to 20 MeV/nucleon will be provided. The LINAC can accelerate protons and heavy ions as well, enabling a variety of experiments.

SPES (Selective Production of Exotic Species) is another European ISOL facility, albeit on a smaller scale, to be constructed in Legnaro, Italy. As shown in Fig. 8, an 8 kW ISOL target with a 40 MeV proton beam induces fission at a rate of $10^{13}s^{-1}$. Post acceleration is accomplished by the existing superconducting linear accelerator complex.

HIE-ISOLDE (High Intensity and Energy ISOLDE) is an upgrade program of the current REX-ISOLDE facility at CERN [11]. In contrast to Spiral2 and SPES, high-energy proton beams of 1.4 GeV or 2 GeV will be used to produce RI's by spallation reactions or fission. Increase of the RI beam energy from 3.3 MeV/nucleon to 10 MeV/nucleon will be attained by upgrading the post accelerator. The beam intensity will also be increased by raising the beam power from 3 kW to 13 kW.

2.2.2 PLANS IN ASIA AND NORTH AMERICA

Several plans for ISOL-based RI beam facilities exist in Asia and North America. Figure 9 shows a schematic diagram of ANURIB (Advanced National Facility for Unstable and Rare Isotope Beams) planned to be built in Kolkata, India. Its first stage is the construction of a 50 MeV superconducting electron linac and a photo-fission ion source coupled with ISOL. The second stage, expected from 2017, contains post accelerators and a storage ring. This project is in collaboration with TRIUMF, where a plan to build a photo-fission based ISOL facility, ARIEL (Advanced Rare Isotope Laboratory) is in progress. The electron drivers in both the facilities share a common design. The expected fission rate is $10^{14}s^{-1}$

Another Asian project along the same line is Beijing ISOL, which is still in the planning stage. It is currently planned to have two ISOL drivers: an electron linac and a research reactor. Post acceleration will be performed by a series of linacs.

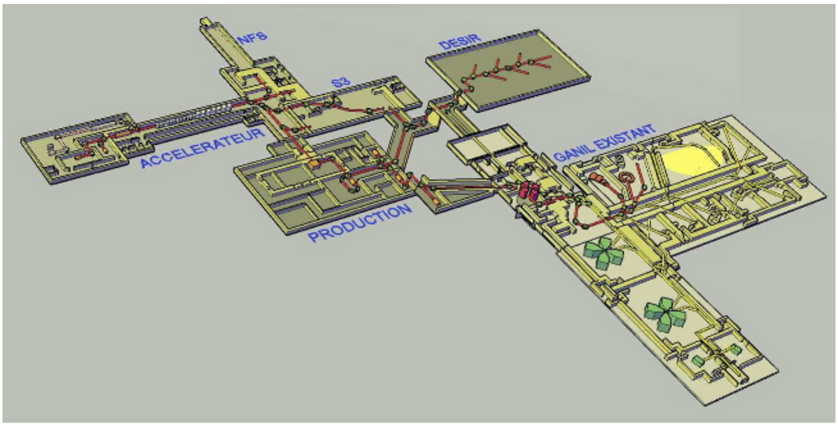

Figure 7. Schematic view of Spiral2 coupled with the current GANIL facility.

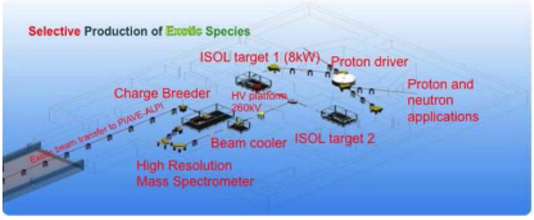

Figure 8. SPES facility at Legnaro.

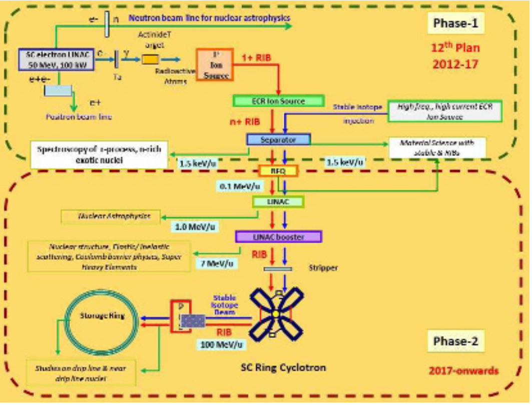

Figure 9. Schematic diagram of the Indian facility ANURIB to be built in Kolkata.

3 Discussion and summary

Since their first realization in 1980's, RI beams have provided a new frontier to nuclear physics and nuclear astrophysics. Reactions involving short-lived nuclei have become within reach of experimental study. Owing to the technical development in producing high-intensity RI beams, nuclei farther from the stability have become available, and exotic features of nuclear structure, such as neutron halos, disappearance (appearance) of classical (new) magic numbers and various new behaviors of neutrons and protons in a nucleus, have been discovered. Many reactions involved in explosive stellar or primordial burning have been studied experimentally.

Based on the successful development of studies with RI beams, new generation facilities have been planned to enhance RI beam intensities, and hence, to enlarge our territory of experimental studies on the nuclear chart as well as to approach explosive nuclear-burning processes in astrophysical events.

The RIKEN RI Beam Factory, one of the new generation facilities, is now in operation. Although the capability of RI-beam production is yet to be optimized, its performance is already intriguing. Newly proposed facilities set their goals for the RI production capability at higher and higher levels. The maximum beam power, which is not directly related to the RI-beam intensity, should give a rough idea of it (the present value for the RIBF is about 10 kW). The design goals of the maximum beam power for future facilities are, for example, 400 kW for FRIB are 5 MW for EURISOL, which are much higher than RIBF. Such an important but tough challenge might help to extend our knowledge of the atomic nucleus and of nuclear interactions. Nuclear matter properties with large proton-neutron asymmetry will also be within experimental reach.

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