ISOL- and In-Flight-based production of rare isotopes

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The main goal of nuclear physics is to unravel the fundamental properties of nuclei composed of a finite number of strongly interacting fermions of two kinds that constitute its building blocks called nucleons: the protons (Z, the charge) and the neutrons (N). Three of the four interactions in nature, the strong, the electromagnetic and the weak forces, are at play in the nuclear system. The strong interaction in the nuclear medium cannot be treated perturbatively and the number of nucleons is not large enough for the use of statistical methods. Although large progress has been done in the recent time with ab-initio calculation to describe the nuclear behavior from first principles, so far, we do not have a theory able to describe the nuclear mesoscopic system from light to heavy nuclei. It is vital to achieve a thorough understanding of the complex structure of nuclei and the nuclear reactions in our laboratory and be able to induce their behavior in astrophysical scenarios. In addition, nuclei also constitute a unique laboratory for a variety of investigations of fundamental physics, which in many cases are complementary to particle physics. Large experimental and theoretical efforts are made world-wide to address the open questions of nuclear physics. Following the 2017 European long-range strategy these questions were formulated as: How does the complexity of nuclear structure arise from the interaction between nucleons? What are the limits of nuclear stability? How and in which astrophysical scenario are the chemical elements produced?

In order to address and progress in the answer to these questions the scientific community is continuously developing new and more sophisticated tools at the level of accelerators and detectors. Research with radioactive ion beams has in the last decades entered in a new era with the advent of energetic beams of radioactive nuclei.

In 1919 E. Rutherford was the first to transmute one element into another. He observed the production of hydrogen by sending alpha articles into nitrogen gas. In 1932, J. D. Cockroft and E.T.S. Walton repeated this experiment using an accelerated alpha beam. They knew that in order to overcome the Coulomb barrier and produce reactions they would need energies of the order of the MeV. They were the first to apply beams accelerated by a dc device to produce a nuclear reaction. Using known voltage-multiplication schemes they succeeded in carrying out cross-section measurements of proton and alpha induced reactions on a number of nuclei. This achievement was followed by an impressive development in accelerator.

From the beginning of nuclear physics, it was clear that the decay of nuclei into their descendants, isobar or alpha-daughter, closer to stability was a source of identification of new species as well as to obtain information of their nuclear structure. The information was limited though to natural radioactive nuclei. The first radioactive nuclei, ^{13}N and ^{30}P, produced by reaction of two stable ones, aluminum, ^{27}Al and boron (^{10,11}B), was obtained in 1934 by I. Curie and J.F. Joliot. Enrico Fermi got the Nobel prize in 1937 by his "demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons". Soon after, in 1938, and after four years of detailed studies by the chemist O. Hahn and F. Strassmann and the physicist L. Meitner, fission was discovered when barium was identified by bombarding uranium with neutrons. L. Meitner and her nephew O.R. Frisch gave the physics interpretation of this reaction process. The first fission reactor was built by E. Fermi in Chicago in 1942 based in the use of uranium oxide and graphite as neutron moderator. It went critical 2nd of December 1942 demonstrating the first laboratory-created nuclear chain reaction. This was the beginning of the identification and study of many neutron rich radioactive nuclei produced in neutron capture reactions.

The advent of powerful accelerators has been crucial for the exploration of the nuclear chart. First light-ion and later on heavy-ion induced fusion reactions were used for the production and study of new isotopes. In particular heavy-ion reactions are very successful in exploring the unknown territory due to the specific N/Z dependence of the line of stability most combinations of stable projectiles and targets produces neutron-deficient nuclei in the region of heavy masses. These reactions are rather selective with only a limited number of channels. This is an important difference with respect to the spallation, fragmentation and fission reactions where hundreds of nuclei are produced. The question is how to isolate one of the scarcely produced short lived species from the overwhelming production of the other nuclei closest to the valley of stability. The ISOL-method and the In-Flight are two complementary techniques to achieve this goal. Both methods transport the produced species to a lower background zone where the nuclear properties are explored in an adequate experimental setup.

The final aim of the different facilities is the production of exotic beams, usually called Radioactive Ion Beam (RIB), as intense and pure as possible. For that we need to achieve the highest production rate, an efficient manipulation of the reaction products, fast delivery as we are dealing with short-lives species and high selectivity. These are therefore the figures of merit of the facilities dedicated to the production of nuclei. In the following we will give a short description of the two methods and the different facilities presently using them as well as a short description of the plethora of upgrades of existing as well the new facilities in construction.

The ISOL-Method

In 1951, a new method of studying exotic nuclei was developed, bombarding an uranium target with fast neutrons coming from the breakup of a 11 MeV deuteron beam. Noble gases were produced by fission, after thermalization in the target these were ionized and electromagnetically separated [O. Kofoed-Hansen and K.O. Nielsen, Phys Rev 82 (1951) 96]. The full process of production, ionization, mass separation and implantation in the detector setup for their study was done in a continuous way, the so-called Isotope Separation On Line technique was born. In ISOL method the radioactive products are thermalized in the target and then re-accelerated. The resulting beams have an emittance, energy resolution and time structure of excellent quality. But the thermalization process and the re-ionization are slow processes in the range of ms to s leading to severe losses for short-lived nuclei and can be very inefficient for refractory elements. These problems can be mitigated if the slowdown process occurs in gas catcher leaving the ions in a 1^+ state as successfully demonstrated in IGISOL (Ion guide Isotope Separator On-Line) the heart of the Facility at JYFL, Finland. Besides the excellent optical quality of the low energy radioactive beams, the possibility of using a thick target increases the production considerably and it has allowed for the detailed study of exotic nuclei down to ms half-life, in spite of the losses in the target. Studies of ground and isomeric state properties in the same element, probe of fundamental interactions and exotic decay modes are performed for many nuclei. The figures of merit of this type of installation are: intensity of the primary beam, fast release of the target products, sensitivity and selectivity. The success of radioactive beams produced in ISOL facilities triggered the interest in producing post-accelerated low-energy to energies up to Coulomb barrier and even beyond for reaction studies of for instance astrophysical interest. However, the realization of this dream had to wait until 1989, when for first time in Louvain-la-Neuve the first post-accelerated beams were produced by coupling the two cyclotrons with an isotope separator, and the astrophysical interesting proton capture of ^{13}N was studied up to energies of 0.63 MeV/u [P. Decrock et al., Phys Rev Letts 67 (1991) 808]. A picture of the principle of the ISOL method with the main elements is given in figure 1.

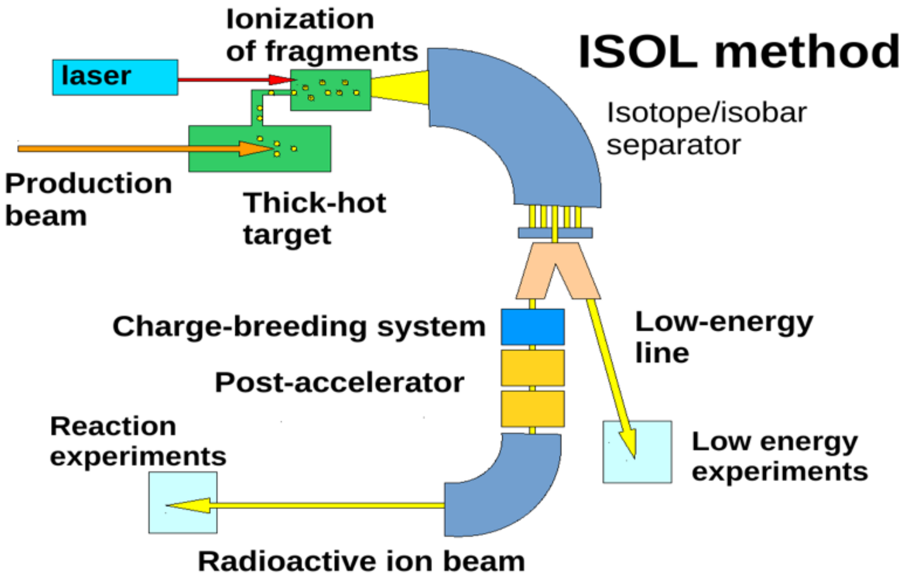

Figure 1 A schematic view of the main elements of the ISOL-Method is shown. The RIB production depends of the energy and intensity of the primary beam and the choice of target and ion source for chemical selectivity and fast release. The shortest delivered nuclei have a half-live in the ms-range. The isotope mass separator will help to deliver pure tailed made species to experiment.

Presently three major ISOL facility exist in the World producing a large variety of beams, two in Europe CERN-ISOLDE and GANIL-SPIRAL and TRIUMF in North-America. The oldest and still the one with the largest variety of beams and continuously pioneering new devices to stay at the forefront of nuclear studies, ISOLDE [Focus on Exotic Beams at ISOLDE: A laboratory portrait, Journal of Physics G: Nucl. Part. Phys. 44 (2017) 094002; https://iopscience.iop.org/journal/0954-3899/page/ISOLDE%20laboratory%20portrait] makes use of the high energy and intensity of the proton beam from the CERN accelerator complex impinging on a large variety of thick targets including uranium carbide. Different types of ion sources are available, surface, plasma and resonant ionization Ion sources (RILIS). The latter is element and even isotope selective assuring high purity beams. The beams extracted from the ion source up to a voltage of 60 KV is further purified by the use of a mass separator. Since 2001 post-accelerated beams are available and more than one hundred different beams were used for experiments. In 2018 the energy upgrade to 10 MeV/u was accomplished as part of the high Intensity and energy upgrade of the facility, the HIE-ISOLDE.

The TRIUMF Isotope Separator and Accelerator (ISAC) facility uses a 500 MeV proton beam of up to 100 μA intensity steered onto one of two production targets to produce radioactive isotopes that are sent to the low-energy beam transport (LEBT) electrostatic beam line and sent via a switchyard to either the low-energy experimental area in the ISAC-I facility or to a series of room-temperature accelerating structures in the ISAC-I medium-energy experimental area. For high-energy delivery, the drift tube linac (DTL) beam is deflected along an S-bend transfer line to the ISAC-II superconducting linear accelerator (SC-linac) for acceleration above the Coulomb barrier (5-11 MeV/u). The continuous improvement of the RILIS ion source together with the recent license for the use of uranium carbide targets bombarded at higher and higher intensity (with permission up to 40 micro-Amp) have led to the production of many new elements and a substantial increase of the intensities delivered.

The SPIRAL1 facility make use of the GANIL coupled cyclotrons as a driver to produce heavy ion beams to impinge on a thick graphite target. The fragmentation products are ionized in a permanent magnet electron cyclotron resonance (ECR) ion source. This scheme is very simple but limits the production to noble gases plus oxygen and fluorine now enlarged to include the alkali elements. These beams can be post-accelerated using the CIME cyclotron that also serves as high resolution mass separator of the radioactive beams accelerated up to 20 MeV/u, the highest of the current ISOL facilities.

The In-flight Method

The so-called In-flight facilities are highly successful in exploring the limits of nuclear stability due to the fast delivery to the experimental setup, high transmission and good particle identification. The in-flight approach profits from the kinematics of the reaction producing the radioactive isotopes to separate them. This makes the process very fast facilitating to explore nuclei with extremely short half-life. These are, in general, discovery machines. When inducing, for instance, fission of a heavy nucleus, the two fission products have energies around 100 MeV, if the target is thin enough the fission products will recoil out of the target in a charged state. The conservation of mass and momentum in fusion and fragmentation reaction of heavy ions in light targets made the reaction products to be emitted forward in the beam direction. Thanks to the use of a powerful electromagnetic system called fragment separator combined with degraders where the energy losses depends of the atomic mass or with gas section where velocity focusing takes place, the reaction products can be separated from the incoming beam and a separation of the produced species in A and Z is obtained. Thismethod was pioneered at the Bevalac at Berkeley where in order to accelerate heavy ions to relativistic energies they connected the super-HILAC heavy ion linear accelerator with the bevatron, a synchrotron accelerator half-mile away, In this way, they could study the fragmentation of a 1 GeV/u ^{20}Ne beam. Its real impact became clear with the measurements of the total interaction cross section of light elements [I. Tanihata et al., Phys Lett B206 (1985) 592] that lead to the discovery of halo structure. Due to the broad scientific opportunities the major high energy heavy ion facilities built in the eighties-nineties: GANIL, GSI, NSCL-MSU and RIKEN dedicated more and more of their beam time to radioactive beam production (RIB). The method is schematically shown in figure 2.

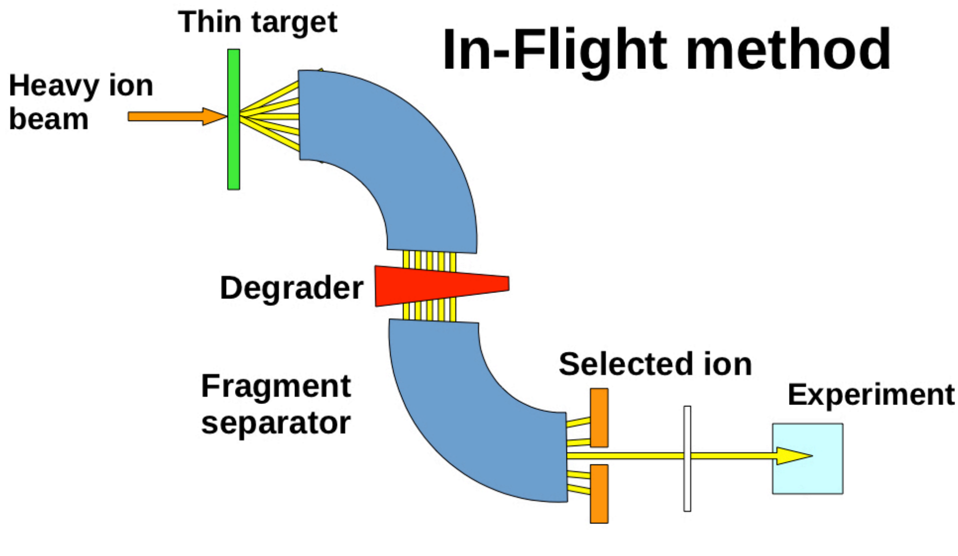

Figure 2. Schematic view of the In-Flight method to produce RIB. The advantage of this method are the chemical blindness and the very fast delivery that allow the delivery of the very short-lived species. To preserve the kinematic focusing the target have to be thin what limits the intensity of the produced nuclei.

The GANIL driver consist of two room temperature cyclotrons that produces heavy ions from C to Ar up to 100 MeV/u and accelerate masses up to U to 25 MeV/u. High intensities of several microamp can be delivered but the final RIB intensities are limited by the weak forward focusing at intermediate energies. Production and selection efficiencies are larger at NSCL-MSU and RIKEN where the fragments separators A1900 and RIPS were specifically built for efficient RIB selection.

The NSCL-MSU facility uses two coupled super-conducting cyclotrons with K=500 and 1200 MeV. It is a unique facility with in-flight separation, stopping, and since September 2015 with reacceleration of rare isotopes at ReA3. The first scheduled experiment with a rare-isotope beam produced by the coupled cyclotrons, separated with the A1900, thermalized in N4, charge-bred in the EBIT and then reaccelerated by ReA3 was used to carry out an experiment with the active target time projection chamber (AT-TPC). More than 900 beams have been used for experiments up to antimony (Z=51). The A1900 is a third-generation projectile fragment separator composed of 40 large diameter superconducting multipole magnets and four 45° dipoles with a maximum magnetic rigidity of 6 Tm. The A1900 has large solid-angle, acceptance of 8 msr, a momentum acceptance of 5.5%, and can accept over 90% of a large range of projectile fragments produced at the NSCL. The cyclotrons with stop operation at the end of 2020 to couple FRIB. In the transitional time the ReA3/6 will possibly be operative.

The GSI Facility combines a high intensity Universal linac, UNILAC, with the heavy ion (Schwer Ionen) Synchrotron, SIS18, added in 1990 that allows for acceleration of ions up to 2 GeV/u. Although the intensity is less than the one produced by cyclotrons it is partially compensated by the high energy of the incoming beam that produces larger forward focusing of the reaction products and the high efficiency of the fragment separator.

The radioactive Ion Beam Factory (RIBF) at RIKEN, Japan couples since 2007 four cyclotrons between the old ring cyclotron (k570 and fixed frequency ring cyclotron) and a new facility that includes the intermediate ring cyclotron and the Superconducting ring cyclotron, SRC K2600 obtaining intense, up to 80 kW, heavy ion beams with light ions accelerated up to 400 MeV/u and up to 345 MeV/u for a uranium beam. This facility has taken the lead as part of the “next generation” of in-flight facilities delivering in 2007 the most intense ^{48}Ca beam of 200 particle micro-Amp and with continuous improvements aiming to reach micro-Amp intensities of uranium beams. A super conducting fragment separator, BigRIPS, is used for selecting the radioactive beams.

To profit from the best of in-flight and ISOL facilities in the quest to achieve high quality beams of short-living radioactive ions one can slow down the fast-radioactive beam in a gaseous catcher leaving the beam in a 1+ charge state. This is the aim of for instance, the SLOWRI ring. The construction started in 2013, It consist, of SLOWRI two kind of gas catchers, He gas catcher with RF carpets for ion guide and Ar gas catcher with resonant laser ionization. The precise mass measurements of trans-uranium elements have been successfully performed using the SLOWRI prototype and multi-reflection time-of-flight mass spectrograph (MR-TOF). First results in the region of Z=100 have already been published [Y. Ito et al., Phys Rev Lett 120 (2018) 152501].

Figure 3 shows the evolution of discovery of nuclei plotted on the two-dimension nuclide chart with protons on vertical axis and neutrons on the horizontal one. The grey background corresponds to the possibly existing nuclei. The chosen years for display correspond to the start of the ISOL-method, the use of in-Flight method by different facilities and present situation.

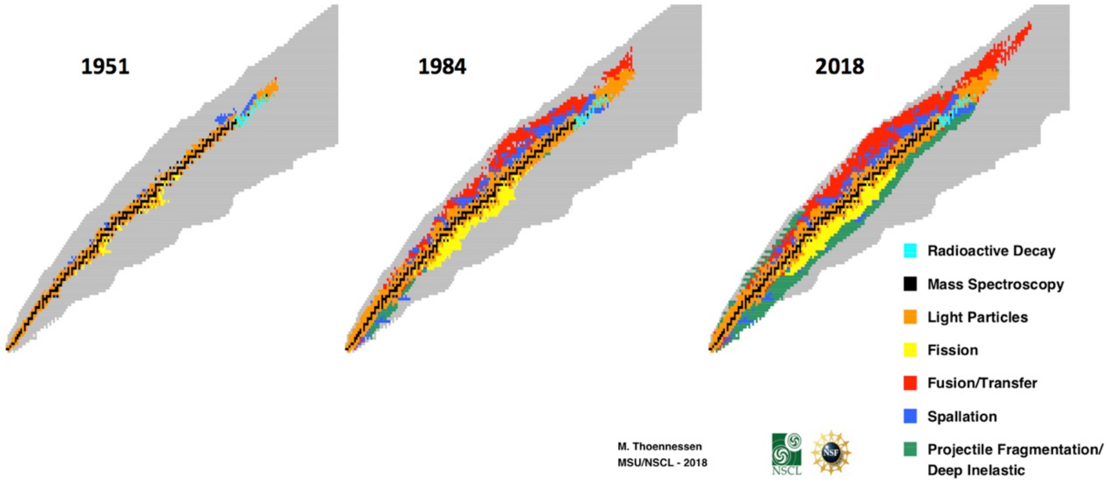

Figure 3 The two-dimension plots with protons on y-axis and neutron on x-axis, courtesy of M. Thoennessen, show in grey the expected nuclei. On the left plot, the nuclei known prior to the use of the ISOL-method where reaction with light particles and some spontaneous fission allow for the production of the 900 nuclei known. The central plot shows the 2257 nuclei known prior to the use of in-flight method. Neutron deficient nuclei were produced by fusion-evaporation, fission, fragmentation and spallation in thick targets. The nuclei chart on the right shows the situation in December of 2018 with 3302 nuclear species identified [M. Thoennessen, International Journal of Modern Physics E 28 (2019) 1930002]. The advancement into the so-called "Terra Incognita" thanks to the in-flight facilities is outstanding.

Future Facilities and Upgrades:

In the following I will mention the new facilities and upgrades. As each facility mixes different techniques in the quest to explore and characterize the limits of nuclear chart, they will be described in the following by alphabetic order.

The **Advanced Rare Isotope Laboratory (ARIEL)** at TRIUMF. The ISAC facilities will be enlarged and complemented with ARIEL including an electron-linac. The targets will be bombarded either with protons or with electrons allowing for a real multiuser facility at the maximum intensity per rare isotope. The operation of the three production stations will allow to fully exploit the numerous existing experimental devices at ISAC. At the heart of ARIEL is a superconducting electron accelerator (e-linac) for isotope production via photo-production and photo-fission as well as a second proton beam line from TRIUMF's cyclotron for isotope production via proton-induced spallation, fragmentation, and fission. The e-linac was built and produced the first accelerated electron beam in 2014. They have implemented and made operative in 2019 the high-resolution mass separator. In order to have a wider range of post-accelerated beams an EBIS charge breeding device has been built and will be used for physics in 2020. The target design to stand the full power is progressing well. The facility will produce first science with the e-linac in 2023 and the three parallel RIB will be operative in 2026.

FAIR (Facility for Antiproton and Ion research) located by GSI is the most ambitious nuclear physics project in construction in Europe. The research at the facility includes four pillars: physics of hadrons and quarks in compressed matter (CBM). Hadron structure and spectroscopy, strange and charm physics with anti-protons (PANDA), Atomic, Plasma Physics and Applications (APPA), and the one of interest here the structure of nuclei, physics of NUclear Structure and Astrophysics research with RIB (NUSTAR). The core of FAIR is the new superconducting synchrotron SIS100 with magnetic rigidity of 100 Tm and circumference of 1100 meters which will deliver high intensity primary beams of 10^{12} ^{238}U at 1.5-2 GeV/u, two to three orders of magnitude higher intensity than the SIS18. The heart of NUSTAR will be the new fragment separator Super-FRS that will improve the transmission and efficiency in a broad range of masses. An increase of a factor of ten thousand in intensity with respect to GSI production is expected. The existing GSI accelerators UNILAC and SIS18 will serve as injectors to SIS100. Attached to SIS100 there are a complex systems of storage-cooler rings and experimental stations. The beams can be used directed for reaction studies in R3B (Reactions with Relativistic Radioactive Beams), degraded to low energies to do High-resolution in-flight SPECtroscopy studies with AGATA and other cutting-edge devices in HISPEC and fully stop for the decay spectroscopy studies (DESPEC), mass measurement (MATS and ILIMA) as well as radii and moments measurements by laser spectroscopy (LASPEC). All these activities are part of the modularized start version that should be operated in 2025.

The Facility for Rare Isotopes Beams (**FRIB**) builds upon the expertise and achievements of the National Superconducting Cyclotron Laboratory (NSCL) at MSU. Since 2001, NSCL's coupled cyclotron facility has been conducting experiments on rare isotopes. FRIB looks beyond NSCL to envision the use of fast, stopped, and reaccelerated rare isotope beams produced by fragmentation to yield consistently high intensities of beams in minimal beam development times. The driver of FRIB will be a 400 kW Linac delivering beams up to 200 MeV/u. The technical construction started in 2014 and the civil construction is also complete. The FRIB fragment separator should be able to accommodate 400 kW and allow ion-by-ion identification. It will have three stages, one high power pre-separator and two high resolution parts for production and delivery of exotic beams. It will have fast, slow with ReA6 and stop experiments and it will start the experimental program in 2022.

HIAF: The Heavy Ion Research Facility at Lanzhou (HIRFL), in Lanzhou, China, is facility focusing on nuclear physics, atomic physics, heavy ion applications and interdisciplinary researches. Based on the developments and experience with heavy ion beam accelerators, a new project HIAF was proposed in 2009. The facility is being designed to provide intense primary and radioactive ion beams. The HIAF project consists of ion sources, linac accelerator, synchrotrons and several experimental terminals. The Superconducting Electron-Cyclotron-Resonance ion source (SECR) is used to provide highly charged ion beams, and the Lanzhou Intense Proton Source (LIPS) is used to provide H_2^+ beam. The superconducting ion Linac accelerator (iLinac) is designed to accelerate ions with the mass to charge ratio, A/q = 7 (e.g. $^{238}U^{34+}$) to an energy of 17 MeV/u. Ions provided by iLinac will be cooled, accumulated and accelerated to the required intensity and energy (up to 1×10^{11} and 800 MeV/u of $^{238}U^{34+}$) in the Booster Ring (BRing), then fast extracted and transferred either to the external targets or the Spectrometer Ring (SRing). It is also planned to equip BRing with a slow extraction system for a wide range of applied researches in biology and material science. As a key part of the HIAF complex, SRing is designed as a multifunction experimental storage ring. An electron target with ultra-low temperature electron beam will be built for Dielectronic Recombination (DR) experiments. Both stochastic cooling and electron cooling systems are going to be incorporated in order to provide high quality beams for experiments and compensate energy losses of internal target experiments. Highly purified radioactive beams can be extracted from SRing for nuclear physics experiments.

HIE-ISOLDE at CERN: In order to broaden the scientific opportunities of ISOLDE far beyond the present reach. The HIE-ISOLDE project provides major improvement in the energy of the post-accelerated beams as well as in the intensity, selectivity and quality of the exotic beams. The project started in 2010 with the design of a super-conducting Linac to be connected to the existing REX-LINAC. The first cryomodule was installed and the first experiment realised in 2015. The energy upgrade including four cryomodules was operative in 2018 reaching energies of 9.5 MeV/u for A/q = 4.5. Acceleration of more than one hundred different beams has been obtained along the years. The intensity upgrade will profit from the new CERN injectors, LINAC4 that will start operating in 2021 and the increase of energy to 2 GeV of the proton beam of the CERN-

PSB (Proton Synchrotron Booster). The higher energy of the proton beam will increase the fragmentation and spallation cross reaction in a factor of 2 to 10. With the increase of Intensity in a factor of 4 global factor up to a factor of 30 can be expected for the production of certain species. This increase in power on target require new beam dumps and steering magnet to deflect the beam to ISOLDE that will take place in the next CERN technical stop in 2024. The improved beam quality and purity depends of different advances some of them already implemented as the solid-state lasers of the RILIS ion source and the RFQ cooler, ISCOOL. Pending is the addition of a second experimental hall to host a new target-ion unit connected to cooler and a high-resolution mass separator. An extension of the existing hall to allocate a storage ring connected to HIE-ISOLDE is also foreseen.

ISOL@MYRRA: The Belgian atomic energy center, SCK-CEN, is actively working on designing, developing and realizing a multifunctional research installation in Mol. MYRRHA is an innovative accelerator driven system that consists of a subcritical nuclear reactor driven by a high-power proton accelerator (600 MeV, 4 mA). In 2008 the idea was proposed to use part of the proton beam to produce intense high purity radioactive ion beams: ISOL@MYRRHA. ISOL@MYRRHA will mainly focus on experimental programs needing long beam times in order to achieve sufficiently-high statistics in precision experiments or to hunt for very rare phenomena. In 2018 the Belgian government decided to support the construction and exploitation of the first phase of the MYRRHA project, as well as the further development of subsequent phases. Phase I comprises a single-injector 4 mA 100 MeV LINAC and a proton target facility of ISOL type. The construction of this ISOL target station, with all required infrastructure will mark the starting point of the realization of ISOL@MYRRHA phase I that should be operative for 2026.

The Radioactive Ion Beam Factory (**RIBF**) is in continuous evolution with its three injectors: RIKEN heavy-Ion Linac, RILAC operative since 1980, AVF from 1989 and RILAC2 from 2011. The energy is boosted by four ring cyclotrons, the RRC, K540 and the fixed frequency Ring Cyclotron (fRC) K570 from 1986. In 2006, the fRC was upgraded to K700 and two more were added, Intermediate-stage Ring Cyclotron K980 and the Superconducting Ring Cycclotron K2400. This complex conforms the so-called new facility, together with BigRIPS, more details can be read in [Y. Yano, NIMB261 (2007) 1009]. The fragment separator, BigRIPS is characterized by two major features: large acceptances and a two-stage separator scheme. The large acceptances are achieved by the use of superconducting quadrupoles with large apertures. This feature enables efficient RI-beam production, even when the in-flight fission of uranium beams at 350 MeV/nucleon is employed as a production reaction. The two-stage separator scheme allows one to deliver tagged RI beams: The first stage of BigRIPS separator serves to produce and separate RI beams, while the second stage serves to identify RI-beam species in an event-by-event mode. The steady increase of primary beam current over the years is plotted in figure 4. In the near future they plan increase the intensity of the Uranium beam by a factor of ten or more. Key to the improvement is the ion source, and losses in the acceleration. To reduce the losses in the charge stripper (a foil) an innovative solution will be realized involving a charge stripper ring. The beam will circulate by the stripper ring until it reaches the required charge state. If successful a factor of ten improvement is expected. They also expect to reach with other improvements in the up to 2000 pnA. In the quest of superheavies it is planned to build a Super-Rilac for injection.

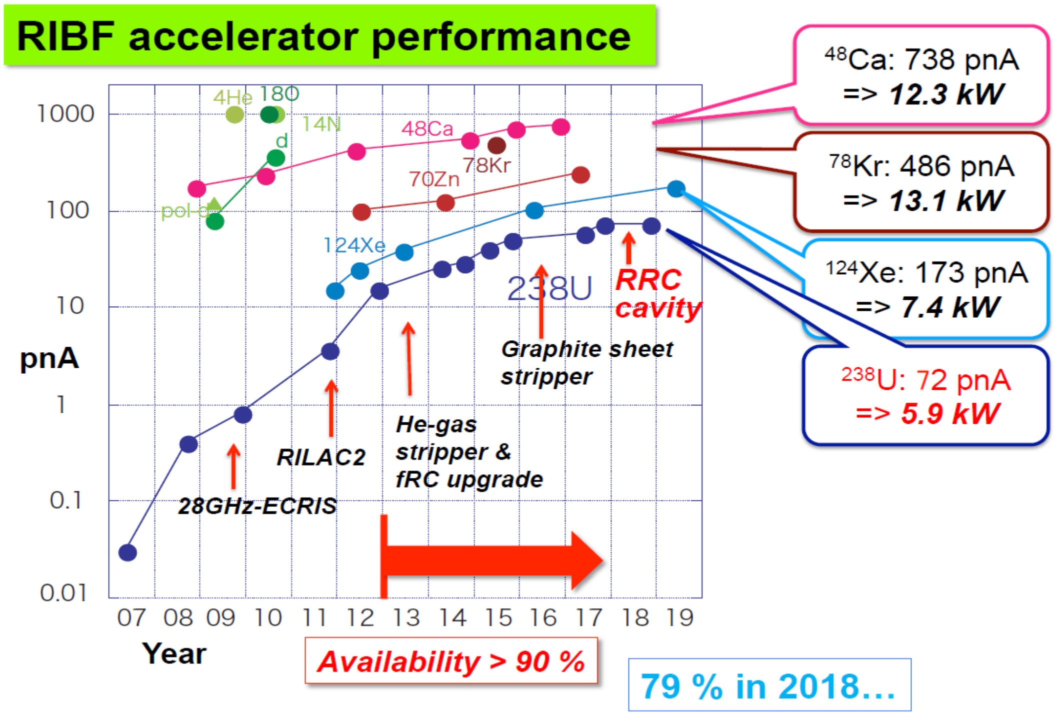

Figure 4. Steady grow of the primary beams in RIBF. The increase and availability of different beams is associated with the improvements of different parts of the machine: ECRIS Ion source, RILAC2, different strippers and in the Riken Ring Cyclotron complex.

Korea is building from zero a large facility: Rare Isotope Science Project (**RISP**). It is constructing equipment and facilities for the Rare isotope Accelerator complex for ON-line experiments (RAON). RAON is a large basic science research facility built around a heavy-ion accelerator. The heavy-ion accelerator is aiming to produce new rare isotopes by greatly accelerating and then protons or heavier ions into targets. RAON will combine the ISOL and In-flight Facilities in the same site for the production of rare nuclei. RAON is a very ambitious project since cutting-edge superconducting radio frequency (SRF) technology is used to manufacture the entire linear accelerator systems.

SPES (Selective Production of Exotic Species): new mid-term facility dedicated to the production of neutron-rich nuclei by fission. It will have a 70 MeV cyclotron as proton driver with two ports for a total current of 750 micro-Amp. One of the ports will be us of production of medical isotopes and the other for OSOL- production. They will us a Uranium Carbide target, ion source and a high-resolution mass separator. The superconducting PIAVE-ALPI accelerator has been upgrade and will be use as radioactive beam re-accelerator. A similar cyclotron has been purchased at i-Themba Labs in South Afrika for production of medical isotopes leaving the existing SSC for nuclear physics.

SPIRAL2 at GANIL: The aim here is to have a multi-beam driver in order to allow both ISOL and low-energy in-flight techniques. The driver of SPIRAL2 facility is a high-power continuous wave (CW) superconducting LINAC delivering up to 5 mA of protons up to 33 MeV and deuterons at 40 MeV and heavy ions up to 14.5 MeV/u. The construction of a new injector for the SPIRAL2 Linear Accelerator is planned in order to expand the range of available high-intensity beams up to Uranium. The heavy ion beams will be used to produce in-flight nuclei with the Super Separator Spectrometer (S3), neutron-deficient exotic nuclei and very heavy nuclei via fusion evaporation reactions. Light neutron rich nuclei will be produced via transfer reactions. The low energy exotic nuclei (few keV/u) produce at S3 and at the existing SPIRAL1 facility will be studied in the new experimental hall DESIR (Decay, Excitation and Storage of Radioactive Ions). The high neutron flux produced by the deuteron beam will be use at the Neutron for Science facility for applications and reliable nuclear data evaluation. While writing these lines I got the good news that the proton beam at the SPIRAL2 LINAC has been accelerated to its nominal value in November 2019. The facility will be in full swing in 2021 reaching the expected maximum power of 200 kW. The main goal will be to study the limit of existence and the structure of nuclei in unexplored middle and heavy mass regions of the chart of nuclei. The DESIR hall will be ready for experiments in 2024.

Superheavy factory (**SHE**) in Dubna, Russia. The production of superheavy elements uses fusion reactions. Both cold and hot fusion has allowed to reach the heaviest elements from Z=106 to Z=118. The heaviest elements have been produced in GSI (Germany), RIBF, RIKEN (Japan), and JINR FLNR in Dubna (Russia). The success in using hot fusion with ^{48}Ca beams to synthesize the heaviest elements known has prompted the construction of a new facility dedicated only to the study of superheavies. The factory is based on a high intensity cyclotron DC-280 that was commissioned in March 2019 and that should start operation in December 2019. A factor of ten in intensity is expected. It will operate as an stand-alone machine able to accelerate ions from carbon to uranium up to 4-8 MeV/u.

A totally different approach is taken by the facility being built at Romania the **ELI-NP**: Extreme Light Infrastructure - Nuclear Physics facility that will operate two components: (i) A very high intensity laser system, with two 10 PW laser arms able to reach intensities of 10^{23} W/cm^2 and electrical fields of 10^{15} V/m. (ii) A system with maximum gamma energy of 19.5 MeV with spectral density: 10^4 ph/s/eV and ~ 0.1 % bandwidth. For the production method the photons scatter on high energy electrons. ELI-NP will allow both combined experiments between the high-power laser and the gamma beam and stand-alone experiments with nine experimental areas. In March 201, ELI-NP has reached the highest laser power level ever produced on Earth. In December 2019, they will perform measurements with tera-watt photon beam ramping up the power to be able to do experiments in June-July 2020 with 10 PW. The experiments with the gamma beam will have to wait until 2023.

Summary: In this contribution I have summarized the existing and planned large Nuclear Facilities. The production of new exotic nuclei and its study is essential to advance the field. The nucleus is a multibody system that has many facets. One nucleus is not important enough to drive the field. Systematic studies on the evolution in N and Z has built-up and driven the field. The present and future of RIB science is very bright, I do not think it has been a time ever when so many facilities are operative, in upgrade process or built new. Most of them will be fully operative in 2025. These efforts are driven by the scientific potential of RIB and have been matched by similar developments in instrumentation that have intentionally not been mentioned here. RIB became the workhorse for nuclear structure and reaction helping to unveil the nuclear interaction in matter and have also become an essential part of nuclear astrophysics. The recent proof of one of the r-process production scenarios, neutron star mergers via multi messenger identification give extra pressure in the production, identification and determination of fundamental properties of neutron-nuclei along the r-process beyond the present knowledge. Different facilities and experimental techniques need to be applied to solve a specific problem. The progress in Nuclear Physics presents a wide front to elucidate the nucleon-nucleon interaction and all phenomena it can create. The complementarity of the methods is important. The operation of these new facilities will increase the present rate of discovery of fifty new nuclei per year. At this rate, we will need up to 66 years to produce all the possibly existing nuclei. The number of years will certainly be reduced with the operation of all the new facilities. In this long way, new phenomena will appear and need to be unveiled keeping RIB science at the forefront of research.