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# Present and future RNB facilities in Europe

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**Abstract**

This contribution starts with a short summary of how the experimental knowledge about exotic nuclei has developed over the years. It then gives an overview of the present and future radioactive beam facilities in Europe. The organization of the work towards the next generation RNB facilities in Europe is presented at the end. 

*Keywords:* Exotic nuclei; Radioactive beams; In-flight techniques; Post-acceleration

## 1. Introduction

Current nuclear physics focuses on exploring nucleonic matter under extreme conditions, which can be created in modern accelerator laboratories. The opportunities offered by beams of exotic nuclei for research in the areas of nuclear structure physics and nuclear astrophysics are exciting and the world-wide activity in the construction of different types of radioactive beam facilities bears witness to the strong scientific interest in the physics that can be probed with such beams.

In this contribution I shall give a short review of the present and future RNB facilities in Europe. In 1997 a NuPECC working group, with the task to produce a report 'spelling out clearly the main options for second-generation radioactive-beam facilities in Europe', was set up. The task of the working group was to investigate facilities that should aim for radioactive beam intensities 1000 times higher than in the running facilities, or facilities in the commission stage. If it is found that more than one facility is needed to cover the foreseen physics issues, they should be truly complementary, and they should be second to none world-wide. The report prepared by the working group is now ready and will be published as a NuPECC report [1]. During the work with the report, a number of RTD projects, financed from the European Community, have been started. I shall give some

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comments on how the work will be organized in the coming years to arrive at a final joint European initiative for the future of the physics on exotic nuclei.

Before this I shall give some examples on how the experimental studies of exotic nuclei have developed over the past few decades.

## 2. 1966, 1980, 2000...

The first conference devoted to the physics of nuclei far from stability, now known as the ENAM conferences, was organized in Lysekil in Sweden [2] in 1966. The participants in this meeting represented the main part of the international expertise and they were allowed to speculate over the new possibilities that could be offered with an on-line facility. Many of the ideas brought up at this meeting were later realized and some largely surpassed. It is interesting to note that already at the Lysekil meeting the possibility of post-acceleration of radioactive isotopes was mentioned.

Another series of conferences, known under the acronym EMIS, were devoted to discussions about techniques and applications of electromagnetic isotopes separators. In 1980 the EMIS-10 conference was organized by the chairman of this conference in Zinal, Switzerland [3]. At the Zinal meeting one could look back to the ideas presented at Lysekil and compare them with the achievements made since then. I shall here continue this by giving some examples which may serve to illustrate how our field has developed since 1980.

- It was a rather safe prediction in 1966 that beta-delayed neutron emitters should be produced when the on-line technique became available. This would then allow for detailed studies of this, at that time, exotic decay process. The expectation was fulfilled and high-resolution energy spectra could be measured with high-pressure $^{3}$He spectrometers. In 1980 one had just been able to identify the two other exotic beta-delayed decay modes, namely, beta-delayed two-neutron and three-neutron emission. Since then, the neutron-rich nuclei have shown two even more exotic decay modes. The first beta-delayed triton emission was observed in $^{11}$Li. The second process, beta-delayed deuteron emission, was found in the decays of the two nuclides $^{6}$He and $^{11}$Li. Both these nuclei are borromean halo nuclei. The energy available for this process is

$$Q_{\beta\mathrm{d}}(A,Z) = 3.004 - S_{2\mathrm{n}}(A,Z)\ \mathrm{MeV} \tag{1}$$

  showing that only nuclei with small two-neutron separation energy, one condition to form a halo state, will show this decay mode.
- The mechanism behind beta-delayed proton emission was well understood in 1980 and at that time more sophisticated experiments were started where protons were used as probes to understand the structure of exotic nuclei. Average excited states lifetimes and nuclear level densities in complex spectra could be determined from the proton spectra. Since then the quenching of the Gamow–Teller strength has been studied for the $sd$ shell nuclei $^{32-35}$Ar. Another example is the recently measured positron–neutrino correlations in the $0^+ \to 0^+$ decay of $^{32}$Ar, which have been used to give improved constraints on the scalar weak interaction.

- Alpha decay of nuclei close to $(Z, N) = 50$ had been observed at the GSI on-line mass separator the years before the EMIS meeting. One may compare this development with the almost 30 cases of *proton* radioactive nuclei found in recent years. They provide a very sensitive determination of the position of the proton dripline up to high masses since they cover the region from $^{105}$Sb to $^{185m}$Bi.
- In 1980 one reported that the exotic doubly-magic nucleus $^{132}$Sn had been studied carefully in beta-decay experiments of $^{132}$In at Studsvik and ISOLDE. Today we have seen the discovery at GSI and GANIL of the other doubly-magic tin isotope, $^{100}$Sn. Recently the discoveries of $^{48}$Ni (GANIL) and $^{78}$Ni (GSI), have been reported. An interesting open question is if the nucleon numbers 20, 28 and 50 really are magic in these outskirts of the nuclear penninsula.
- New regions of deformation had been discovered at the CERN PS, at ISOLDE and Grenoble around $^{32}$Mg, the $(Z, N) = (40, 60)$ region and in heavy Rb and Cs isotopes. In recent years one has been able to find several nuclei showing octupole shapes among heavy Fr and Ra nuclei.
- Nuclei with $T_Z < 0$ was discussed in Lysekil. In 1980 the experimental technique had come far enough to produce the $T_Z = -2$ nucleus $^{32}$Ar. It was known from a few counts of beta-delayed protons, stemming from isospin-forbidden proton decay from the isobaric analogue state in $^{32}$S. Today we can do full spectroscopic studies of the $T_Z = -5/2$ nucleus $^{31}$Ar where the data includes beta-delayed two-proton emission.
- Nuclear masses are, of course, interesting to investigate over broad regions over the nuclear chart. One method is to measure $Q_\beta$-values but this is both difficult and time-consuming. In 1980 progress had been made with a Mattauch–Herzog spectrometer. Today nuclear masses are determined with techniques that give very high precision out to the dripline regions. The Penning trap and the MISTRAL spectrometer at ISOLDE and the storage ring ESR at GSI are examples.
- In 1980 it was realized that exotic nuclei are of high relevance for nuclear astrophysics. Today we have, for example, seen reaction experiments at Louvain-La-Neuve relevant to the break-out reactions, as for example $^{13}$N(p, $\gamma$)$^{14}$O and $^{19}$Ne(p, $\gamma$)$^{20}$Na. Another example is given by the waiting-point nuclei $^{130}$Cd and $^{129}$Ag produced and studied at ISOLDE.
- One field that is new since 1980 is the nuclear solid state physics programme conducted at ISOLDE. With a large variety of different techniques as perturbed angular correlations, Mössbauer spectroscopy, emission channeling, CESVEC, DLTS and PL, problems like the metallurgy of alloys at the microscopic level and the structure and mobility of impurity/vacancy complexes may be studied.

It was also around 1980 that the first experiments with fragmentation of heavy ions started. The pioneering experiments were done by T.M.J. Symons and his coworkers at Berkeley but the real strength of the technique was not realized until later. One my see this from the very vague statements made by Symons at the conference in Helsingør in 1981 [4]:

"...we questioned the applicability of high-energy heavy ions to this field (...) our experience leads us to believe that this question does indeed have a positive answer.

If the physics interests justifies it, then high-energy heavy-ion beams can certainly be expected to play a role in the study of nuclei at the limits of stability…"

But it was first in 1985, when the measurements of total interaction cross section for He and Li isotopes at Berkeley became available, that the field got a tremendous boost. The reason for this was that the data could be interpreted as due to halo states in $^{6}$He and $^{11}$Li. This started an intense activity both experimentally and theoretically. The in-flight techniques have since then become the major actor in investigations of the structure of and reactions with exotic nuclei. On the European scene the heavy-ion beam facilities GANIL and GSI, with their fragment separators LISE3 and FRS have been the principal actors.

Another very important development is the nuclear theory which at present has a huge interest in exotic nuclei. For a detailed account of this development I refer to the recent NuPECC report [1].

## 3. Radioactive nuclear beam facilities in Europe

I shall here give a short overview of the present and planned RNB facilities in Europe.

Two basic methods can be used to produce Radioactive Nuclear Beams (RNB), which are depicted in Fig. 1. One is commonly called Isotope Separation On Line (ISOL) and the other is called In-Flight. In an ISOL-type facility, radioactive nuclei are produced essentially at rest in a thick target, a catcher or an ion guide, bombarded with particles from a primary source or driver accelerator. After ionisation and selection of a specific mass by electromagnetic devices, these nuclei are accelerated in a post-accelerator. For the In-Flight method, an energetic heavy-ion beam is fragmented or fissioned while passing through a thin target, and the reaction products are subsequently transported into a secondary target after mass, charge and momentum selection in a fragment separator. Since the reaction products are generated in flight, no post-acceleration is required.

The ISOL method produces high intensity and high quality RNBs generally at energies up to 25 MeV/u. The lifetimes of the accelerated radioisotopes are limited downwards by their extraction time from the target and their transfer time to the ion source. In-Flight facilities are optimum for higher energy (above about 50 MeV/u) beams of very short-lived (down to hundreds of ms) nuclei. These beams can be collected and cooled to high phase-space density beams in storage rings using various cooling methods. The resulting beams from the ISOL and In-Flight RNB facilities are highly complementary, and both types of facilities are necessary for pursuing the scientific goals of the nuclear physics community.

### *3.1. In-Flight RNB facilities in Europe*

In western Europe, two In-Flight RNB facilities are operational, at GANIL, Caen, France, and GSI, Darmstadt, Germany. The GANIL cyclotrons produces heavy-ion beams up to 95 MeV/u, with a present maximum beam power of 2 kW and plans to raise this value to 6 kW. The heavy ions are fragmented in a high-power thin target, preceded and followed by superconducting magnetic lenses, the so-called SISSI device, which increases

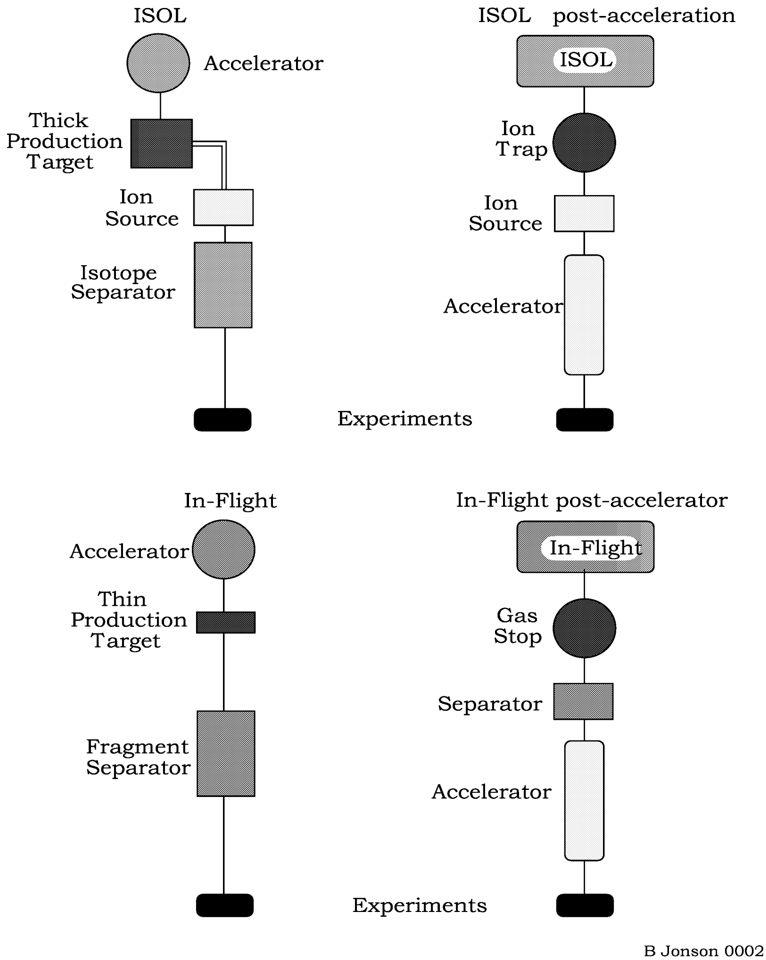


Fig. 1. The basic methods of producing radioactive nuclear beams. Above: the ISOL method with associated post-accelerator to the right. Below: the In-Flight method along with associated post-accelerator.

the useful secondary beam intensities by at least one order of magnitude. The fragments are collected and identified in the LISE device, whose performances have been considerably improved with time. At the GSI, heavy-ion beams up to uranium are accelerated at energies up to 1 GeV/u by the UNILAC linac and the SIS synchrotron. These beams are fragmented or fissioned in a thin target, and the fragments are collected and identified in the Fragment Recoil Separator (FRS). They can either be studied in the focal plane of the FRS, or cooled in the ESR storage and cooler ring, where very precise measurements of the RNB masses and lifetimes can be performed.

In eastern Europe, the Flerov Laboratory at Dubna, Russia, operates two cyclotrons, U400 and U400M, whose beams can be fragmented, and the resulting nuclei studied at the separators ACCULINNA and COMBAS.

### 3.2. ISOL RNB facilities in Europe

In Europe, a broad range of first generation ISOL RNB facilities have been developed, which provide a good basis for defining the design goals for next generation facilities. One can regroup the existing and planned RNB facilities in Europe according to the driver accelerator or primary source for producing the radioactive nuclei, and to the post-accelerator which deliver the radioactive beams from rather low energies up to about 25 MeV/u.

#### 3.2.1. Combination of a driver cyclotron and a post-accelerating cyclotron

The prototype of such a combination is the RNB facility at Louvain-la-Neuve, Belgium, which was the first in the world to deliver post-accelerated RNBs and which is running since 1989. It uses a driver low-energy cyclotron, producing 30-MeV protons with intensities up to 200 mA on target, i.e. with a maximum beam power on the target of 6 kW; the post-accelerator is a $K = 110$ cyclotron, which acts at the same time as isobaric mass analyzer. RNBs not very far from the line of stability are thereby produced, with high intensities (up to $2 \times 10^9$ particle/s) and at energies from 0.65 MeV/u up to 12 MeV/u for some beams, which have mostly been used for studying questions relevant to nuclear astrophysics. This facility has recently been upgraded by the commissioning of a new post-accelerating cyclotron, which widens its energy range suitable for nuclear astrophysics from 0.2 to 0.8 MeV/u.

The SPIRAL facility at GANIL, Caen, France, belongs to the same category. The driver accelerators are the GANIL cyclotrons delivering heavy ion beams at energies up to 95 MeV/u, with a maximum beam power on the target of 6 kW. The post-accelerator is a new cyclotron CIME, which also acts as isobaric mass selector, and which delivers RNBs between 1.7 and 25 MeV/u. The SPIRAL is at the writing moment of this report just ready to start its experimental programme.

#### 3.2.2. Combination of a driver proton synchrotron and a linac as post-accelerator

The front runner in this category is ISOLDE/CERN, Genève, Switzerland, which for more than 30 years has been delivering a broad spectrum of isotopes with 60 keV beam energy, and have been used in a wide variety of experiments ranging from Nuclear Physics through Nuclear Astrophysics to Solid State Physics. The driver accelerator is the PS booster, with delivers a 1.4 GeV proton beam with an average intensity up to 2 μA, the maximum beam power deposited in the production target being about 2 kW.

ISOLDE will be extended to energies up to 2.2 MeV/u by post-accelerating the ISOLDE beams with a linac. The new facility, called REX-ISOLDE, will be operational in year 2001.

The SIRIUS project, planned to be placed at the Rutherford Appleton Laboratory, Didcot, United Kingdom, belongs to the same category. It proposes to use an 800-MeV 100-mA proton beam from the ISIS synchrotron to produce the radioactive nuclei, the maximum beam power on the presently developed RIST target being about 50 kW. The post-accelerator would be a CW-linac, producing RNBs up to 10 MeV/u.

#### *3.2.3. Combination of a driver cyclotron and a tandem for post-acceleration*

The LNS, Catania, Italy, is building the EXCYT facility, which will use the existing superconducting heavy-ion cyclotron as driver accelerator, a new 200-MeV proton driver being also considered. The post-accelerator will be the existing 15 MV tandem, which requires negative ions; it will allow to emphasise experiments which will require RNBs with well defined energies between 0.2 and 8 MeV/u.

#### *3.2.4. Combination of a reactor as driver and a linac as post-accelerator*

There exists several front runners in the production of low-energy fission fragment beams, like the OSIRIS facility at Studsvik, Sweden. Post-acceleration of fission fragments was first planned at the high flux reactor of the ILL, Grenoble, France, and the project was called PIAFE. This concept was later transferred to the high-flux reactor under construction at Munich, Germany, where, under improved conditions, the new fission fragment accelerator MAFF is being built up. The post-accelerator will be a linac, producing intense neutron-rich RNBs up to 7 MeV/u.

Besides thermal neutrons from a reactor, fast neutrons from the break-up of deuterons may also be used for the production of radioactive nuclei in a $^{238}$U target. This scheme is presently explored within the European RTD programme SPIRAL Phase II.

## 4. R&D work in the coming years

The two methods used in RNB facilities to produce beams are substantially different and are entirely complementary. While ISOL facilities allow good-quality low-energy RNBs to be produced, In-Flight facilities are optimum for higher-energy beams of very short-lived nuclei. One of the conclusions in the NuPECC report [1] is that both types of facility are necessary for pursuing the scientific goals of the nuclear physics community. It is clear that if an ISOL facility is to be built which can deliver beams which are a factor 1000 more intense than anything currently planned, then considerable development work is needed. An upgrade of the present GSI Facility is also envisaged for the next few years.

The identification of the work and its execution will be the next task. This will be facilitated by the support of the EU to some RTD projects which will be operational at the beginning of this year. These are:

*EURISOL* A preliminary design study of the next-generation European ISOL radioactive nuclear beam facility. This project will include nine European laboratories and last two years with an EU budget of 1.5 M€.

*CHARGE BREEDING* Charge Breeding of intense radioactive beams. This project will include seven European laboratories and last three years with an EU budget of 1.2 M€.

*R3B* A next-generation experimental set-up for Reaction studies with Relativistic Radioactive Beams. This project will include eight European laboratories and last two years, with an EU budget of 0.8 M€.

*EXOTAG* Studies of EXOtic nuclei using TAGging spectrometers. This project will include eight European laboratories and last four years, with an EU budget of 1.5 M€.

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