The EURISOL report - A feasibility study for a european isotope-separation-on-line radioactive ion beam facility

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THE EURISOL REPORT

A FEASIBILITY STUDY FOR A
EUROPEAN ISOTOPE-SEPARATION-ON-LINE
RADIOACTIVE ION BEAM FACILITY

December 2003

The EURISOL Report

A FEASIBILITY STUDY FOR A EUROPEAN ISOTOPE-SEPARATION-ON-LINE RADIOACTIVE ION BEAM FACILITY

Co-ordinated by Prof. Jean Vervier

Report to the European Commission

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NuPECC: Nuclear Physics European Collaboration Committee
UCL: Université Catholique de Louvain

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Executive Summary

The present report includes a synthesis of the work carried out within the EURISOL contract – funded by the European Commission – by ten major European Nuclear Physics laboratories. The detailed results of this work are contained in the reports of the five Task Groups, in Appendices A to E.

The EURISOL project aims at a preliminary design study of the 'next-generation' European Isotope Separation On-Line (ISOL) Radioactive Ion Beam (RIB) facility, which will extend and amplify, beyond the year 2010, the exciting work presently being carried out at the first-generation RIB facilities in Europe and other parts of the world, in the fields of Nuclear Physics, Nuclear Astrophysics and Fundamental Interactions.

In this document, the scientific case for high-intensity RIBs using the ISOL method is first summarised, more details being given in Appendix A. It includes (a) the study of atomic nuclei under extreme and so-far unexplored conditions of composition (i.e. as a function of the numbers of protons and neutrons, or the so-called isospin), rotational angular velocity (or spin), density and temperature; (b) the investigation of the nucleosynthesis of heavy elements in the Universe, an important part of Nuclear Astrophysics; (c) a study of the properties of the fundamental interactions which govern the properties of the Universe, and in particular of the violation of some of their symmetries; (d) potential applications of RIBs in Solid-State Physics and in Nuclear Medicine, for example, where completely new fields could be opened up by the availability of high-intensity RIBs produced by the ISOL method.

The 2 methods for production of RIBs, i.e. the ISOL and In-Flight methods, are also described, their complementarity is underlined and the present world-wide situation with respect to RIB facilities, including the short-term projects, is presented. This points towards the need for 'next-generation' infrastructures such as the proposed EURISOL facility, with intensities several orders of magnitude higher than those presently available or planned

The proposed EURISOL facility is then presented, with particular emphasis on its main components: the driver accelerator, the target/ion-source assembly, the mass-selection system and post-accelerator, and the required scientific instrumentation. Specific details of these components are given in Appendices B to E, respectively.

The driver accelerator investigated in this study is a 1-GeV, multi-MW, superconducting proton linear accelerator, although the implications of enabling it to accelerate light heavy ions with charge-to-mass ratios of 1/2 and 1/3 were also considered. An alternative suggestion – i.e. an electron accelerator using brehmsstrahlung to generate photofission – was also examined, but found to have limitations which would make it more expensive for the high yields demanded for EURISOL.

The proposed ISOL facility would use both (a) 100-kW proton beams on a thick solid target to produce RIBs directly, and (b) a 'converter' target to release high fluxes of spallation neutrons which would then produce RIBs by fission in a secondary target. The third method envisaged (c) is similar in concept, but would use a 1–5-MW proton beam on a windowless liquid mercury-jet 'converter' target to generate the neutrons.

The predictions for the expected yields from EURISOL are outlined, as obtained using the best presently-available methods to determine the various factors which will influence the performance. We conclude that the proposed facility will produce beams of radioactive ions with yields which will be one to three orders of magnitude – depending on the nucleus involved – higher than presently available RIBs, and that many hitherto completely unexplored regions of the Chart of the Nuclei will thus become accessible. Typical key experiments within the general scientific fields outlined above, which will then be made possible, are presented as 'boxes'.

A number of different options for the post-accelerator were studied, and the preferred solution is again a linear accelerator, capable of accelerating the RIBs with very low loss to 100 *A* MeV, up to at least ^{132}Sn, for example. At this energy, secondary fragmentation can be done with such neutron-rich nuclei, leading to production of very neutron-rich nuclei that cannot be produced by more conventional single-step processes. Important multi-user considerations are the provision of several simultaneous beams from the mass-separator, the extremely wide range of energies available from the post-accelerator, and the ability to switch post-accelerated RIBs to different experimental areas from successive sections of the post-accelerator.

Before the full engineering design of the proposed EURISOL facility can be performed, Research and Technical Developments (RTD) on some crucial technical points have to be carried out. These have been identified during the course of the present contract, and are detailed in Appendices B to E for the various components of the facility outlined above, and they are also summarised in the present report. Similarly, the possible synergies of EURISOL with other major projects of European scientific communities, both at the level of RTDs and of the possible sharing of some parts of EURISOL with these major projects, have been identified in Appendices A to E and are summarised in the present report. Of particular interest is the possible use of the EURISOL driver accelerator to produce RIBs which then decay to produce neutrino beams with excellent properties – so-called 'beta beams'. This aspect creates unique opportunities for collaboration between the Nuclear Physics and Particle Physics communities. Another interesting spin-off is the ready availability at EURISOL of high yields of new medical radioisotopes which are at present either available only in very small quantities or not at all.

The estimates of the costs of EURISOL, construction and running costs, have been performed in as much details as is presently possible, with some remaining uncertainties. These have been carried out for the various components of the facility, as outlined in Appendices B to E, and are summarised in the present report, together with some additional cost estimates. The total capital cost of the project is estimated to be of the order of 613 M€, within 20%, as outlined in the body of this report. This sum, while large, is not extravagant when compared to the cost of other large-scale national and multi-national facilities. It is important to emphasise that the EURISOL facility would be a European research facility, and would be intended to serve as a hub for a wide multi-national, multi-user community within and beyond Europe.

We are of the opinion that the present phase of the EURISOL project should be followed by two other phases: a number of RTD investigations on the crucial technical points identified as outlined above – perhaps as a Design Study – leading to a full engineering design of the proposed facility. If successful, these two phases would lead to the construction, beyond the year 2010, of a major European Radioactive Ion Beam ISOL facility for the advance of Nuclear Physics, Nuclear Astrophysics and Fundamental Interactions. This will maintain Europe's pioneering position in these fields where many European scientists have in the past played a leading world-wide role.

1 Introduction

1.1 Radioactive ion beams

Nuclear physics – originally a subject of purely experimental and academic interest – has led to untold applications and spin-offs in modern times. Medical technology springs to mind, with radioactive isotopes being used for diagnostic and therapeutic purposes, while particle accelerators are now used routinely for radiotherapy. However, the impact on other fields is enormous, encompassing such disparate fields as power generation, microchip technology, space research and astrophysics. The search for a better understanding of nuclei, and even of the way that matter is synthesised in the Universe, all depend crucially on our knowledge of the physics of the nucleus.

Basic nuclear physics research is delving ever deeper into the unknown, to measure and explain the behaviour of nuclei, and is now reaching out to determine the properties of exotic nuclei, beyond the realm of the stable nuclei, even reaching the 'drip-lines' at the very edge of the nuclear chart. New modes of nuclear decay have been recently observed, while tests of fundamental symmetries, testing and refinement of the Standard Model of fundamental interactions, and exploration of the 'magic' numbers of protons and nuclei in such exotic nuclei are all enticing avenues of discovery.

The study of these radioactive nuclei, involved as they are in nucleosynthesis in the stars and in supernovae, leading to the creation of the very stuff we are made of, has until now been prohibited by their very short lifetimes and the limited yields produced with our present medium-energy accelerators. By using current technology, we are now able to produce accelerators and ingenious systems for producing beams of radioactive ions in quantities which will permit their properties to be measured and understood. The quest for radioactive ion beams (RIBs) which are orders of magnitude more intense than those currently available is the motivation behind the exciting EURISOL project.

1.2 Aim of the project

The EURISOL project aims at a preliminary design study of the 'next-generation' European Isotope Separation On-Line (ISOL)* Radioactive Ion Beam (RIB) facility. The latter will extend and amplify, beyond the year 2010, the exciting work presently being carried out at the first generation RIB facilities, in Europe and all over the world, in the fields of Nuclear Physics, Nuclear Astrophysics and Fundamental Interactions.

1.3 Background to the project

The EURISOL programme finds its origin in the work of the **Nuclear Physics European Collaboration Committee (NuPECC)**, an expert committee of the European Science Foundation (ESF). In 1997, NuPECC issued a report entitled: ***'Nuclear Physics in Europe: Highlights and Opportunities'*** [1]. In addition to a thorough review, in a European perspective, of the recent achievements and future challenges of Nuclear Physics, the report

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* The two ways of producing Radioactive Ion Beams (RIBs), i.e. the Isotope Separation On-Line (ISOL) method and the In-Flight method, are thoroughly described in sub-section 3.1.

includes recommendations, one of which reads as follows: "A study group should be set up in order to investigate the main options for second-generation radioactive ion beam facilities in Europe".

Following this recommendation, a RNB Study Group* was established in 1997, whose work extended over about 2 years, and was summarised in a report entitled ***'Radioactive Nuclear Beam Facilities'*** [2] issued in 2000.

To give a wider global perspective, a Nuclear Physics Working Group, created by the Megascience Forum of the Organisation for Economical Co-operation and Development (OECD), issued a report in 1999 entitled: ***'The OECD Megascience Forum - Report of the Working Group on Nuclear Physics'*** [3].

One of the recommendations it contains reads as follows: "The Working Group recognises the importance of radioactive nuclear beam (RNB) facilities for a broad programme of research in fundamental nuclear physics and astrophysics, as well as applications of nuclear science. A new generation of high-intensity RNB facilities of each of the two basic types, ISOL and In-Flight, should be built on a regional basis. Interested governments are encouraged to undertake the necessary decisions within the next few years, and the facilities themselves should become operational in five to ten years".

The first concrete application of these recommendations in Europe was the launch of a proposal for a major upgrade of the facilities available at the Gesellschaft für Schwere Ionen Forschung (GSI) in Darmstadt, Germany [4,5], recently approved by the German Government. One of the major scientific goals of this 'International Accelerator Facility' at GSI is the production of very intense RIBs by the In-Flight method. When operational, this facility will be the 'next-generation' European In-Flight facility recommended by the OECD Working Group.

The second application of these recommendations, i.e. the first step towards the construction, in Europe, of a next-generation RIB facility based on the ISOL method, is the EURISOL programme, whose general aim is defined at the beginning of this section. This programme started on January 1, 2000, and is supported by the European Commission (EC) under the Research and Technical Development (RTD) contract number HPRI-CT-1999-50001. The present report describes the results obtained within this programme during its 4 years of work (2000–2003).

1.4 Methodology

The EURISOL Steering Committee, which included representatives of each of the participating institutions, identified the following five tasks:

- **Task 1:** The identification of **key experiments** which will be carried out with the planned facility, and of their specific technical needs in terms of the nature, energy and intensity of the required RIBs.
- **Task 2:** The definition of the **driver accelerator** for providing the accelerated particle beams which will produce the radioactive nuclei of interest.
- **Task 3:** The specifications of the **targets & ion-sources** required, where the impact of the beams from the driver accelerator will produce the radioactive species, and where the latter will be transformed into ions.

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*Note: The term 'Radioactive Nuclear Beam' – abbreviated to RNB – is often used instead of the somewhat more accurate 'Radioactive Ion Beam' or RIB.

- **Task 4:** The definition of the **mass-separator and post-accelerator** systems, with which the radioactive ions will be selected according to their masses and accelerated to the required final energies.
- **Task 5:** The identification of the scientific **instrumentation**, experimental apparatus, electronics, etc., which will be required to carry out the key experiments with the RIBs produced.

Five Task Groups were formed to carry out these particular tasks, and the results of their work are thoroughly described in the accompanying Appendices. (We note in passing that some of these reports were essentially complete by the end of 2002, while others needed more time for completion. As a consequence, some recent developments might not be referred to.)

The present report presents an overview which synthesises their work, and includes:

- a description of the scientific need for high-intensity RIB facilities;
- the case for the EURISOL facility;
- a general presentation of the proposed facility;
- its expected performance;
- a few key experiments illustrating the need for EURISOL;
- the R&D which will have to be carried out before the full engineering design of EURISOL can start;
- possible synergies between such a facility and other major European projects;
- cost estimates for the facility; and
- the conclusions drawn from this study.

During the course of the present programme, NuPECC launched the elaboration of a **Long-Range Plan for Nuclear Physics in Europe**, based on and updating the previous report *'Nuclear Physics in Europe: Highlights and Opportunities'* [1]. The conclusions of this work reinforce those of the previous report, particularly where it concerns the next-generation European ISOL RIB facility, i.e. EURISOL. The report on this long-range plan is presently being edited by NuPECC.

The present first phase of the EURISOL programme, carried out within the Fifth Framework Programme (FP5) of the European Commission (EC), should be followed by two other phases:

(1) The completion of R&D studies on some crucial technical points which have been identified during the present phase, to be carried out within the EC's Sixth Framework Programme (FP6) under a **Design Study** contract;

(2) A full **engineering design study** of the facility, to be performed within the Seventh Framework Programme (FP7).

At some stage during this process, a suitable site should be chosen (presumably at an existing large accelerator facility, after which the **construction phase** of EURISOL could start, leading to the full **operational phase** after the year 2010.

2 The Scientific Need for High-Intensity RIBs Using the ISOL Method

In the present section, we outline the scientific case for EURISOL, i.e. the strong motivations behind the proposal for constructing a ***next-generation*** **European Radioactive Ion Beam (RIB)** facility based on the **Isotope Separation On-Line (ISOL)** method. We summarise the current problems in Nuclear Structure, Nuclear Astrophysics and Fundamental Interactions which can be tackled by using RIBs. The present section is based on the report of the Key experiments Task Group (**Appendix A: The Physics Case for EURISOL**, attached to the present EURISOL Report) and on many other documents [1-7]. These documents present a thorough overview of the large number of scientific questions which can be tackled with RIBs, and include many more experiments to be carried out with next-generation RIB facilities than are listed in this present section. We therefore refer the reader to these documents for a more detailed account of the reasons behind the very strong interest presently shown by the international Nuclear Physics scientific community in the use of Radioactive Ion Beams. In this respect, a brochure on RIBs published by NuPECC is particularly enlightening, and is supplied together with the present report.

2.1 Nuclear structure at the extremes

The nucleus, a many-body quantal system with Z protons and N neutrons (i.e. with a total number of nucleons $A = Z + N$), can be characterised by several quantities. Some of these are the numbers A, Z and N, and the third component of the isospin $T_z = (N\text{-}Z)/2$, the total angular momentum J (in units of Plank's constant $\hbar$), the excitation energy E or a parameter related to the level density, the temperature T (measured in MeV), and the nucleon density ρ in terms of the 'normal' nuclear density $\rho_0 = 0.37\ \text{fm}^{-3}$. Since the birth of Nuclear Physics, the properties of nuclei have been explored for values of T_z, J, E, T and ρ not very far from the 'normal' ones, i.e. T_z for stable nuclei, small values of J, E and T, and ρ close to ρ_0. Current problems in Nuclear Structure deal with the properties of nuclei for extreme values of these quantities, very far from the 'normal' ones, where completely new phenomena are anticipated, as will be illustrated in the following.

a) Nuclei very far from stability

The present status of the Nuclear Chart, in which the numbers of protons Z and neutrons N are plotted on the vertical and horizontal axes, respectively, is shown in figure 2.1. The nuclei indicated by black squares are stable, while red squares indicate β^+-emitters, blue squares β^--emitters, yellow squares α-emitters, and green squares spontaneously fissioning nuclei. The so-called **proton and neutron drip-lines**, also shown in figure 2.1, limit the region where nuclei are stable against the emission of protons and neutrons, respectively, whereas for very heavy nuclei, the limit arises from (fast) fission, leading to the idea of **fission drip-lines**. The precise locations of these limits themselves are highly uncertain, since they arise from the extrapolation from the properties of known nuclei, by using various models whose predictions sometimes differ considerably. With these reservations, the expected number of nuclei which are stable against nucleon emission and (fast) fission is about 5000, whereas the number of known nuclei (black and coloured squares in figure 2.1) is only about 2500. The remaining nuclei – about 2500 of them – represent the so-called ***'terra incognita'***, the unexplored regions of Nuclear Structure with respect to isospin, and its exploration is one of the main present challenges of Nuclear Structure. As will be shown in the present report, the 'next-generation' RIB facilities, both ISOL and In-Flight, will allow us to explore far into this *terra incognita*.

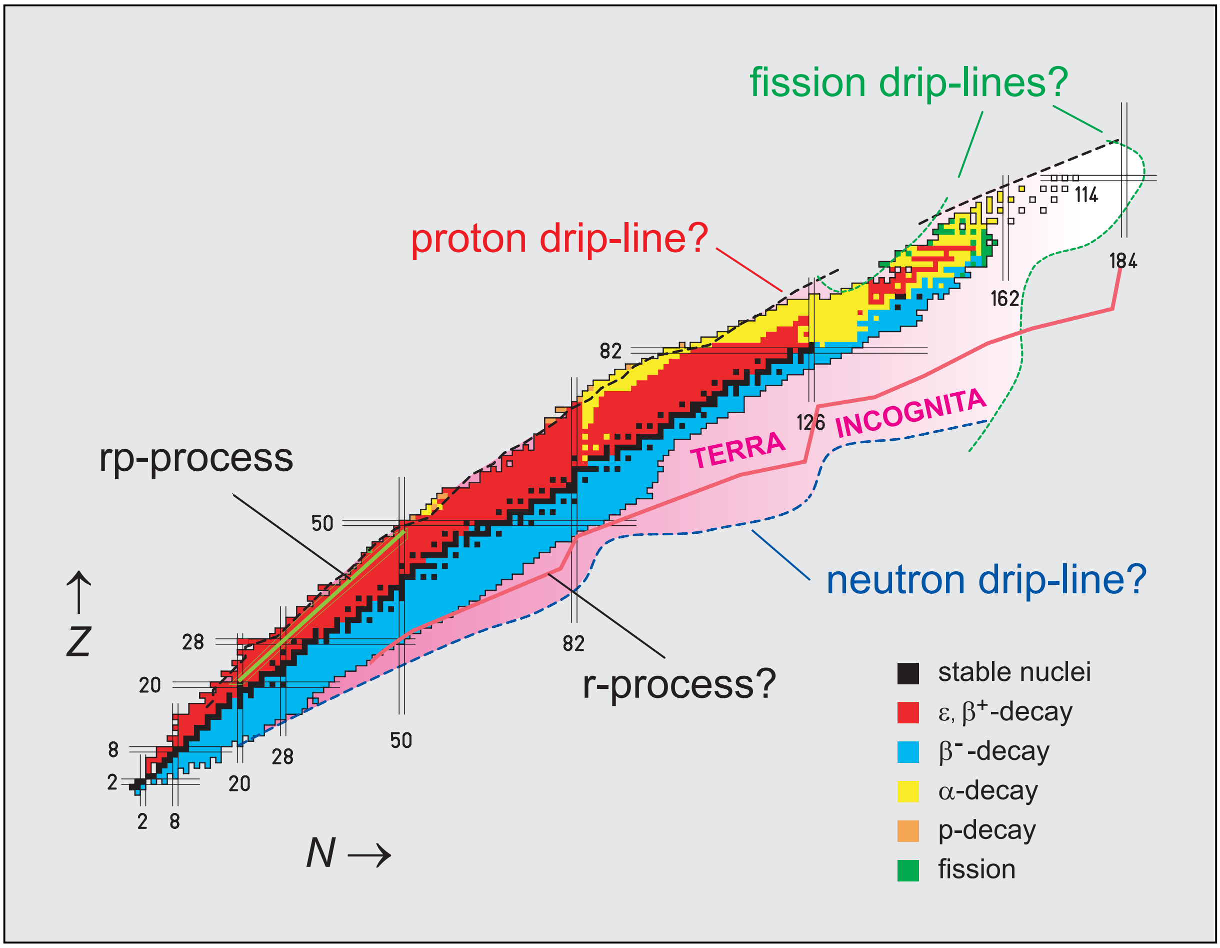


Fig. 2.1: Map of the nuclear landscape.

Completely new phenomena are expected to occur very far from stability, as is thoroughly detailed in Appendix A: '*The Physics Case for EURISOL*', and in other documents [1-7], and as is illustrated below. However, as is usual in Science, properties of nuclei in the *terra incognita* are likely to be discovered which are completely unexpected at the present time.

As noted above, the positions of the **drip-lines** in figure 2.1 (the 'shores' of the *terra incognita*) are very uncertain, and their experimental determination is a problem of much current interest. The **proton drip-line** is reasonably well known up to about mass 200, but the **neutron drip-line** is only identified up to fluorine, whereas the **'fission' drip-line**, for very heavy and **superheavy elements**, is completely unknown. As will be shown in the next section, the availability of very intense neutron-rich RIBs is a very promising method to approach, and hopefully reach, the neutron drip-line up to medium mass nuclei. These beams will also lead us to a better understanding of the region of very heavy and superheavy elements.

Even if the drip-lines cannot be reached all around the 'shores' of the *terra incognita* by using RIBs, penetrating deeply into this unknown area of the nuclear chart is likely to reveal many new phenomena. One of these is the predicted **changes in the shell structure**. All models presently used to describe the properties of known nuclei are ultimately based on the **Shell Model**, in which, as a first approximation, the nucleons are assumed to move independently of each other in a mean field generated by all of them. This model includes the so-called 'shells' or 'orbits' of. nucleons, leading to 'closed-shell' configurations which are intrinsically more stable than others. It is probable that the shells which have been identified in the known nuclei are considerably different for very exotic nuclei. Hints that this is indeed the case have already been found in light nuclei, for N=20 and 28, and many other similar cases could occur, which need experimental verification.

Another phenomenon which has recently attracted considerable interest is the occurrence of **halos in nuclei**, i.e. regions in some nuclei where the nuclear density is much lower than normal and which occur at very large distances from the centre of the nucleus. Such halo structures are known mostly for neutron-rich nuclei, up to ^{22}C, and should occur in other so-far-unknown regions of the nuclear chart, close to the drip-lines.

Many other phenomena are expected very far from stability, which are detailed in the report of the Key Experiments Task Group. Specific examples of these, which could be investigated with the very intense RIBs of the proposed EURISOL facility, will be presented in section 6.

b) Nuclei at very high spins

Rapidly rotating – i.e. high-spin – nuclei have been studied for about 30 years, and fascinating phenomena have been discovered, such as the wide variety of shapes – prolate, oblate, triaxial, octupole, etc. – acquired by the nucleus, and also so-called **'superdeformation'**, in which the nucleus resembles a rugby ball with a major-to-minor axis ratio of two-to-one, etc. New phenomena are predicted by the models used to describe those already known, and include even more exotic shapes and **'hyperdeformation'**, in which the axis ratio is three-to-one, etc. In order to investigate these phenomena, even higher spins than those which have been reached up to now should be produced and investigated, i.e. about 70$\hbar$. This can only be achieved using very high-intensity neutron-rich RIBs: these beams will allow us to study ultra-high spins in neutron-rich nuclei, where the fission barrier is high enough to allow these states to survive fission, as is shown in detail in Appendix A: '*The Physics Case for EURISOL*', and illustrated by specific examples in section 6.

c) Nuclei at extreme densities and temperatures

Nuclei may exist at densities very different from the 'normal' one, either very low ('dilute') or very high ('compressed'), and at temperatures (expressed in MeV) very different from zero. Under such conditions, nuclear matter has many analogies with fluids, liquids and gases: it is also described by dynamic and thermodynamic methods, including the use of the so-called nuclear **Equation Of State** (EOS), and it displays similar phenomena, such as a liquid-gas phase transition. What is mostly unexplored so far in this field is the influence of the composition of nuclear matter, in terms of the numbers of protons and neutrons, i.e. the influence of isospin. The present situation is comparable to the (very limited) knowledge of the properties of liquids and gases one obtains by ignoring their composition! This new dimension in this field, i.e. the isospin, can only be investigated with very high-intensity RIBs in a wide energy range, up to about 100 MeV per nucleon, as is illustrated in an example in section 6.

2.2 Nuclear Astrophysics and nucleosynthesis

Almost all the elements which make up the Universe, and in particular the solar system, the earth and our own bodies, have been produced through nuclear reactions taking place in stars or during explosive stellar events. One of the main challenges of present-day Nuclear Astrophysics is to understand fully this sequence of reactions, thereby explaining nucleosynthesis. Many of these nuclear reactions involve unstable nuclei, sometimes very far from stability. A complete description of nucleosynthesis thus requires a detailed knowledge of these nuclei and of the nuclear reactions in which they are involved. As will be shown in the present report, the 'next-generation' RIB facilities, both ISOL and In-Flight, will allow us to study these nuclei and nuclear reactions, and will thereby contribute, in a decisive way, to the full understanding of nucleosynthesis.

One of the ways Nature has produced nuclei between iron and uranium is through the r**apid neutron-capture** process (or **r-process)**, in which neutrons with very high fluxes lasting for short times (e.g. in type-II supernovae) are successively captured, building up heavier and heavier nuclei. A possible path of this r-process in the nuclear chart is shown in figure 2.1. It clearly goes deep into the *terra incognita* of very exotic nuclei in the neutron-rich region, whose properties, lifetimes, binding energies and delayed-neutron emission probabilities, are unknown. These properties determine the abundances, in Nature, of the so-called r-elements, i.e. the stable nuclei which result from the multiple β-decays of very exotic nuclei after neutron irradiation. Knowledge of these properties is thus a prerequisite for a full understanding of the nucleosynthesis of about half of the heavy elements between iron and uranium.

Another astrophysical process, which leads to the nucleosynthesis of light and medium-mass proton-rich stable nuclei up to about tin, is the so-called **rapid-proton-capture** or **rp-process**. This consists in successive captures of protons during explosive events involving binary stars (e.g. X-ray bursts), competing with β^+-decays, and running close to the proton drip-line up to about mass 100. In this case, the decay properties of the exotic nuclei involved are reasonably well known, but the cross sections of the important nuclear reactions – mostly proton captures – are not. Their measurements require very high intensities of the exotic nuclei of interest. With the first-generation RIB facilities currently available, such experiments can only be carried out for nuclei not very far from stability, involved at the beginning of the rp-process. The extension of such experiments to more exotic nuclei, necessary for a full understanding of the rp-process, will only be possible with the next generation of RIB facilities, whose beam intensities will be orders of magnitude higher than the first-generation ones.

Examples of key experiments to be performed with EURISOL which pertain to these processes of nucleosynthesis are given in section 6 of the present report.

2.3 Fundamental interactions and symmetry laws

Fundamental interactions are presently described by the so-called Standard Model of electroweak interactions. A major part of the activity in this field searches for new physics beyond the Standard Model. This can be carried out, either by High-Energy Physics experiments, or by very precise measurements in nuclear β-decay, wherein the nucleus is a 'laboratory' for testing the fundamental interactions and their symmetry laws. These precision experiments often involve exotic nuclei and require very high intensities to reach the degree of accuracy necessary to yield significant results. This implies the use of 'next-generation' RIB facilities producing large quantities of low-energy (tens of keV) exotic nuclei.

Four topics in this field have been identified where the availability of high intensities RIBs will open new issues.

- The first is the study of super-allowed β-transitions, which should allow us to test the unitarity of the so-called Cabbibo-Kobayashi-Maskawa (CKM) quark-mixing matrix, which is basic to the Standard Model; this will require very precise determinations of the lifetimes, Q-values and branching ratios of these super-allowed β-transitions in medium-mass (A=62 to 86) exotic nuclei.
- The second is the identification of possible exotic interactions in the nuclear β-decay beyond the traditional vector and axial-vector couplings; this can be carried out through measurements of the β-neutrino angular correlation, in practice by observing the recoil nuclei and its γ-radiation.
- The third is the search for possible deviations from maximal parity violation or from time-reversal invariance in the strangeness-conserving sector of the Standard Model; these tests would involve the production of polarised exotic nuclei and the very precise measurements of the longitudinal polarisation of the emitted β-particles.
- The fourth is the investigation of the parity non-conservation in atomic transitions involving heavy atoms; these experiments would require the storage and manipulations of heavy radioactive atoms such as francium in suitable traps. An example of such an experiment is detail in section 6.

2.4 Potential of RIBs in other branches of science

The main motivation for building next-generation ISOL RIB facilities lies in Nuclear Structure, Nuclear Astrophysics and Fundamental Interactions. However, higher intensities of RIBs are potentially useful in other branches of science, and in particular in Solid-State Physics and in Medical Applications.

The interest of RIBs in Solid-State Physics is testified by the numerous experiments in this field carried out at existing ISOL RIB facilities, and in particular at ISOLDE at CERN in Switzerland. These are summarised in section 20 of the Key Experiments Task Group's report (Appendix A: '*The Physics Case for EURISOL*'). Also presented there are some other possibilities at EURISOL. They are mainly based on the implantation of large quantities of radioactive nuclei deep into a solid, i.e. far from its surface, and at relatively well-defined depths. They also include diffusion experiments, the use of polarised RIBs, studies of semiconductors, etc.

Radioactive nuclei produced at EURISOL would also be used for medical applications, although mainly through isotopes produced as by-products. In particular, radioisotopes extracted from the proposed liquid-mercury target used for neutron production could be selectively implanted in cancer cells for therapy purposes, as outlined in the report of the Target and Ion-Source Task Group (Appendix C: '*Targets & Ion Sources for EURISOL*'). One such application is described in more detail in section 6 of the present report.

3 The Case for a EURISOL Facility

The present section gives a short description of the ISOL and In-Flight methods used to produce RIBs, and underlines their complementarity. The current situation concerning RIB facilities using the two methods in Europe and around the world is then summarised. The need for 'next-generation' RIB facilities is then stressed, together with a brief review of the present proposals worldwide for such facilities. Finally, the European scientific community which would make use of such facilities is evaluated.

3.1 The ISOL and In-Flight methods

There are two basic methods of producing RIBs, which are illustrated in figure 3.1.

- In the ISOL method, very high quantities of radioactive nuclei are produced by bombarding a thick (primary) target with the beam of particles from a first accelerator (the so-called driver accelerator), or with a neutron flux from a nuclear reactor or a spallation neutron source. These radioactive nuclei are then extracted from the target, transformed into ions in a suitable ion source, mass-separated and finally re-accelerated to the desired energies by a second accelerator (the so-called post-accelerator). The RIBs thereby produced are sent to a secondary target, to induce nuclear reactions and perform spectroscopic measurements.
- In the In-Flight method, heavy ion beams, in the energy range from 100 MeV to 1 GeV per nucleon, strike a thin primary target, in which they undergo fragmentation or fission. The fragments produced are selected in flight by a Fragment Recoil Separator, according to their masses and charges. They are then directed onto a secondary target, for spectroscopic and reaction studies.

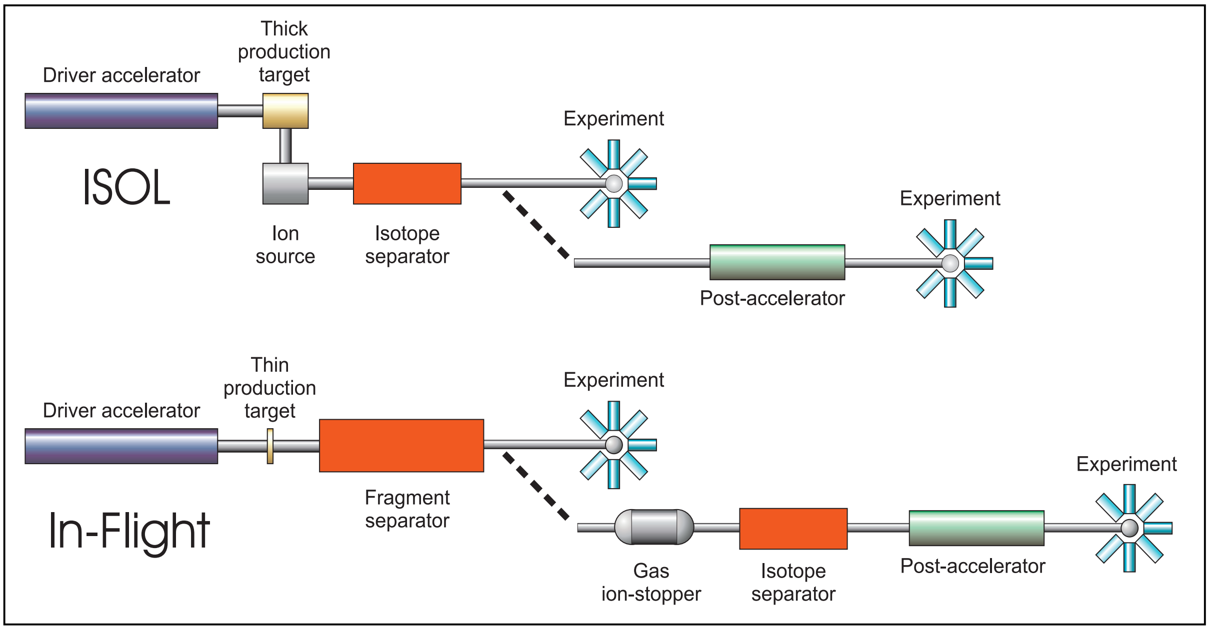


Fig 3.1: Comparison between the ISOL and In-Flight methods of producing radioactive ion beams. Post-acceleration is possible in either case.

These two methods are highly complementary. The ISOL method is limited to RIBs with relatively long half-lives, larger than about 1 ms, owing to the time it takes to extract the radioactive nuclei from the thick primary target and to transport them to the ion source. However, the ISOL method produces RIBs with very good qualities (low emittance and good energy resolution) in a wide range of energies, from a few tens of keV to about 100 MeV per nucleon. The In-Flight method allows one to produce RIBs with very short half-lives, down to a few hundreds of nanoseconds (i.e. just the flight time in the Fragment Recoil Separator). These beams are however of poor quality, and they are restricted to energies close to those of the primary stable beam, in the range of 100 MeV to 1 GeV per nucleon. Beam quality can be improved by using a beam-cooling technique, but this would exclude very short lifetimes.

The two methods can be combined by slowing down the fragments produced by the In-Flight method, and then post-accelerating them, as shown in the lower part of figure 3.1.

3.2 The current situation with respect to RIB facilities

The current global situation with respect to existing RIB facilities using the ISOL method – or those under construction – is shown in table 3.1, while those using the In-Flight method are shown in table 3.2. The upper part of each table lists the European facilities, the lower part, those outside Europe. The starting dates shown in parentheses are the expected ones. For cyclotrons as post-accelerators, the *K*-value yields the maximum energy Kq^2/A, where q is the charge of the accelerated ion and A its mass number. The proposed Rare Isotope Accelerator (RIA) in the USA is not listed in table 3.1, but will be described in section 3.3.

Table 3.1: RIB facilities using the ISOL method and a post-accelerator, either existing or under construction

Location	RIB Starting Date	Driver	Post-accelerator
Louvain-la-Neuve Belgium	1989	cyclotron p, 30 MeV, 200 μA	cyclotrons *K* = 110, 44
SPIRAL: GANIL Caen, France	2001	2 cyclotrons heavy ions up to 95 *A* MeV, 6 kW	cyclotron CIME *K* = 265, 2–25 *A* MeV
SPIRAL-II: GANIL Caen, France	(2008)	s/c linear accelerator LINAG heavy ions up to 40 MeV	cyclotron CIME *K* = 265, 2–25 *A* MeV
REX ISOLDE: CERN Genève, Switzerland	2001	PS booster p, 1.4 GeV, 2 μA	linac 0.8-3.1 *A* MeV
MAFF Munich, Germany	(2008)	reactor 10^{14} n/cm^2.sec	linac up to 7 *A* MeV
EXCYT Catania, Italy	(2004)	cyclotron heavy ions	15-MV tandem 0.2–8 *A* MeV
HRIBF Oak Ridge, USA	1997	cyclotron p, d, α, 50-100 MeV, 10-20 μA	25-MV tandem
ISAC-I: TRIUMF Vancouver, Canada	2000	cyclotron p, 500 MeV, 100 μA	linac up to 1.5 *A* MeV
ISAC-II: TRIUMF Vancouver, Canada	(2005)	cyclotron p, 500 MeV, 100 μA	linac up to 6.5 *A* MeV

Note: The proposed EURISOL facility and the RIA facility proposed in the USA are not listed, but are discussed in section 3.3

Table 3.2 summarises the current global situation concerning RIB facilities using the In-Flight method, either running or under construction. Again, the upper part of the table lists the European facilities, the lower part, those outside Europe. The starting dates between parentheses are again the expected ones. The proposed upgrade of the GSI facility and the part of the RIA proposal pertaining to In-Flight are not listed in table 3.2, and will be described in section 3.3.

Table 3.2: RIB facilities using the In-Flight method, existing or under construction.

Location	RIB starting date	Primary accelerator	Fragment separator
GANIL Caen, France	1985	2 separated-sector cyclotrons up to 95 *A* MeV	LISE SISSI
GSI Darmstadt, Germany	1989	UNILAC + SIS up to 1 *A* GeV	FRS, ESR
Flerov Laboratory Dubna, Russia	1996	2 cyclotrons	ACCULINNA COMBAS
KVI Groningen, Netherlands	(2005)	SC cyclotron AGOR *K* = 600	TRIMP
NSCL East Lansing, USA	19??	SC cyclotron K1200 up to 200 *A* MeV	A1200 Projectile Fragment Separator
NSCL East Lansing, USA	2001	SC cyclotrons K500-K1200	A1900 Projectile Fragment Separator
RIKEN Saitama, Japan	1992	Ring-cyclotron up to 135 *A* MeV	RIPS
RIKEN Saitama, Japan	(2005)	Ring-cyclotrons up to 400 *A* MeV (light ions) up to 150 *A* MeV (heavy ions)	3 fragment separators storage & cooler rings
IMP Lanzhou, China	1997	Separated-sector cyclotron *K* = 450, up to 80 *A* MeV	RIBLL proposed storage & cooler rings (2004)

Note: The proposed GSI upgrade, and the In-Flight part of the RIA facility proposed for the USA, are not listed, but are discussed in section 3.3.

3.3 The next generation of RIB facilities

The operating RIB facilities listed in tables 3.1 and 3.2 have already produced – and those under construction will certainly also produce – very interesting scientific results in the fields of Nuclear Structure under extreme conditions, Nuclear Astrophysics and Fundamental Interactions and Symmetry laws, as outlined in section 2. However, in many parts of the world, 'next-generation' RIB facilities are being planned with beam intensities several orders of magnitude higher than those produced by the facilities listed in tables 2.1 and 2.2, and with a much wider variety of beam species. The reasons for this move towards 'next-generation' RIB facilities have been outlined in many reports [1-7], in particular in the report of the Study Group on RNBs [3], which worked under the umbrella of the OECD Megascience Forum Working Group on Nuclear

Physics and whose conclusions have been endorsed by the latter. These various arguments can be summarised as follows.

Most of the information accumulated so far on the properties of the presently-known nuclei (the black and coloured squares in the Nuclear Chart of figure 2.1) has been obtained through the use of stable beams, accelerated to energies between a few 100 keV and about 1 GeV per nucleon, and bombarding stable targets. Extending the present knowledge towards the presently-unknown nuclei, i.e. far into the *terra incognita* of figure 2.1, would clearly require either radioactive (unstable) targets, or RIBs with intensities comparable to those of the presently-available stable beams. It can be shown [8], on the basis of very general arguments, that the use of RIBs is more efficient than the use of radioactive targets, for half-lives shorter than about 1 hour, which is the case for the vast majority of the radioactive nuclei. The intensities of the stable beams typically range between a few nanoamperes to a few microamperes, i.e. between 10^{10} and 10^{13} particles per second. The presently operating RIB facilities listed in tables 2.1 and 2.2 are far from reaching these values, producing, in the best cases, some 10^{8} to 10^{9} particles per second. The rich scientific fields outlined in section 2 thus require the development of 'next-generation' RIB facilities which will produce beams of radioactive nuclei which will be at least 2 to 3 orders of magnitude higher than the present-generation ones, and approach, in the most favourable cases, those of the stable beams.

This general argument can be made more specific, as outlined in the various reports referenced [1-6] and illustrated by some particular examples in section 6. With beam intensities available in the present-day RIB facilities, the possible experiments described there would become prohibitively long, lasting months and years instead of hours and days. This justifies the world-wide tendency towards 'next-generation' RIB facilities, as evidenced in table 3.3 below.

The OECD Study Group on RIBs, mentioned above [3], also concluded that, in view of the wide scientific fields opened by RIBs, several 'next-generation' RIB facilities of the two basic types, ISOL and In-Flight, should be built on a regional basis. This is illustrated in table 3.3, which displays the projected facilities in North America, Japan and Europe. For the latter, the planned (and recently approved) upgrade of the GSI facility at Darmstadt, Germany [4,5] would fulfil the need for a European 'next-generation' In-Flight RIB facility, whereas the presently proposed EURISOL facility would play a complementary role for ISOL.

Table 3.3. Next-generation ISOL and In-Flight RIB facilities proposed in Europe and the USA.

Location	**Driver**	**Post-accelerator**	**Fragment separator**	**Type of facility**
Europe (Germany) GSI	synchrotron, heavy ions: 1.5 A GeV	-	'Super-FRS'	In-Flight
Europe: EURISOL	protons, 1 GeV, 1-5 MW	SC linac, up to 100 *A* MeV	-	ISOL
USA: (RIA) Rare Ion Accelerator	900 MeV protons heavy ions: 400 *A* MeV, 100 kW	linac 8–15 MeV	4-dipole separator	ISOL, In-Flight

3.4 The European scientific community involved in RIB research

There is intense interest in the use of radioactive beams in Europe, and a growing community of research staff, and postgraduate students who are studying RIBs. It is difficult to assess how many individuals are involved at any one time, since student numbers change from year to year. However, an appreciation of the numbers can be gained by simply listing the (more than 80) European institutes which were represented by attendees at the 'RNB 2000' conference, held in Divonne, France in 2000, 'RNB 2003' held in Argonne, USA in 2003, or the three EURISOL Town Meetings. It can be seen that most Western European countries are heavily involved, along with many others from Eastern Europe. (We have excluded from this list the many attendees from other parts of the world.) It is thus reasonable to conclude that there are over 1000 active members of the European scientific community who are keenly interested in research using radioactive ion beams.

Belgium

Institut de Physique Nucléaire, Université Catholique de Louvain, Louvain-la-Neuve
Departement Natuurkunde, Instituut voor Kern- en Stralingsfysica, Leuven
Physique Nucléaire Theorique et Physique Mathematique, Université Libre de Bruxelles, Brussels

Bulgaria:

University of Sofia St. Kliment Ohridski, Sofia

Croatia:

Division of Experimental Physics, Rudjer Bovskovic Institute, Zagreb

Czech Republic:

Nuclear Physics Institute ASCR, Rez

Denmark:

Niels Bohr Institute, Copenhagen
Institut for Fysik og Astronomi, Aarhus University, Aarhus

France:

CEA DIF service de Physique Nucléaire, Bruyéres le Chatel
Centre Etudes Nucléaire Bordeaux-Gradignan, Gradignan
CSNSM-IN2P3-CNRS, Orsay
Dapnia/SphN-CEA Saclay, Gif-sur-Yvette
Grand Accélérateur National d'Ions Lourds, Caen
Institut de Physique Nucléaire, Orsay
Institut de Recherches Subatomiques Strasbourg, Université Louis Pasteur, Strasbourg
Institut des Sciences Nucléaires UJF-IN2P3-CNRS, Grenoble
Laboratoire de Physique Corpusculaire de Caen, Caen
Theoretical Physics Laboratory, Strasbourg

Finland:

Department of Physics, University of Jyväskylä, Jyväskylä

Germany:

Fachbereich Physik, University of Konstanz, Konstanz
Forchungszentrum Karlruhe, Karlsruhe
Gesellschaft für Schwerionenforschung, Darmstadt
Institute of Theoretical Physics, University of Giessen, Giessen
Section Physik, Ludwig-Maximilians-Univerität München, Garching
Hahn-Meitner Institut, Berlin
Heidelberg University, Heidelberg
Institut für Physik, Johannes-Gutenberg-Universität, Mainz
Institut für Kernchemie, Johannes-Gutenberg-Universität, Mainz

Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt
Institut für Kernphysik, Johann Wolfgang Goethe-Universität, Frankfurt
Institut für Kern und Hadronphysik, Forschungzentrum Rossendorf, Dresden
Institut für Theoretische Physik, University of Erlangen-Nuemberg, Erlangen
Labor für Verschleisstests, Leipzig
Max-Planck Institute for Nuclear Physics, Heidelberg

Hungary:
Institute of Nuclear Research of the Hungarian Academy of Science, Debrecen

Israel:
Department of Particle Physics, The Weizmann Institute of Science, Rehovot

Italy:
Dipartimento di Metodologie Chimiche, Fisiche per l'Ingegneria, University di Catania, Catania
Dipartimento di Matematica e Fisica, Università di Camerino, Camerino
INFN - Laboratori Nazionale de Legnaro, Legnaro
INFN - Laboratori Nazionale del Sud, Catania
INFN & Dipartimento di Fisica, Universita' di Bari, Bari
INFN & Dipartimento di Fisica, Universita' di Catania, Catania
INFN & Dipartimento di Fisica, Universita' di Ferrara, Ferrara
INFN & Dipartimento di Fisica, Universita' di Firenze, Florence
INFN & Dipartimento di Fisica, Universita' di Milano, Milan
INFN & Dipartimento di Fisica, Universita' di Napoli, Naples
INFN & Dipartimento di Fisica, Universita' di Padova, Padua
INFN & Dipartimento di Fisica, Universita' di Udine, Udine
INFN & Dipartimento di Fisica Teorica, Universita' di Torino, Turin

Norway:
Department of Physics, University of Oslo, Oslo
Institute of Physics, University of Bergen, Bergen

Poland:
Henryk Niewodniczanski Institute of Nuclear Physics, Crakow
Department of Physics, IFD, Warsaw University, Warsaw
Instytut Fisiki, Uniwesytet Jagiellonski, Crakow

Portugal:
Departamento de Fisica, IST, Lisbon
CENTRA, Lisbon
Universidade Fernando Pessoa, Porto

Rumania:
Institute of Atomic Physics, Bucharest-Maragele

Russia:
All-Russian Federal Nuclear Center - VNIIEF
Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Dubna
Institute of Spectroscopy, Russian Academy of Sciences, Troitsk
Kurchatov Institute, Moscow
St. Petersburg Nuclear Physics Institute, Gatchina
V.G. Khlopin Radium Institute, St. Petersburg
Voronezh State University, Voronezh

Ukraine:
Institute for Nuclear Research, Kiev

United Kingdom:
CLRC, Rutherford Appleton Laboratory, Didcot
CLRC, Daresbury Laboratory, Warrington
Department of Physics & Astronomy, University of Edinburgh, Edinburgh

Department of Physics, University of Oxford, Oxford
Department of Physics, University of Surrey, Guildford
Oliver Lodge Laboratory, University of Liverpool, Liverpool
School of Engineering, University of Brighton, Brighton

Slovak Republic:
Faculty of Mathematics & Physics, Comenius University, Bratislava

Spain:
University of Santiago de Compostela, Santiago de Compostela
Institut d'Estudis Espacials de Catalunya, Barcelona
Instituto de Estructura de la Materia, CSIC, Madrid
Universidad de Sevilla, Seville

Sweden:
Department of Physics, Chalmers University of Technology, Göteborg
Oerebro Universitet, Oerebro
Stockholms Universitet, Stockholm

Switzerland:
CERN-ISOLDE, Geneva
Division of Nuclear Medicine, University Hospital of Geneva, Geneva
Paul Scherrer Institute, Villigen

The Netherlands:
Kernfysisch Versneller Instituut, Groningen

4 General Presentation of the EURISOL Facility

4.1 The main options

As was shown in subsections 3.1 and 3.2 above, many different schemes for producing RIBs by the ISOL method are conceivable, depending on the type and energy of the particles produced by the driver, on the target and the ion source, on the energy of the RIBs produced by the post-accelerator, etc. For that reason, the EURISOL Steering Committee had to take some decisions concerning the various options during the first phase of the EURISOL project, as will now be outlined.

Figure 2.1 shows that the widest region of unknown nuclei lies on the neutron-rich side of the nuclear chart. The new phenomena expected for very exotic nuclei, mentioned in section 2, such as changes of shell structures, halos and skins, exotic decays, etc., are likely to be found in this region, as is the probable path for the astrophysical r-process. The proton-rich region is however also of strong interest, as shown in section 2, e.g. for the astrophysical rp-process, for studies of Fundamental Interactions, etc. The best way to produce very intense neutron-rich RIBs is through fission, induced by very intense neutron beams. The latter can be produced by spallation induced by high-energy, high-intensity proton beams on a heavy target. For that reason, it was decided that the driver accelerator should be a linear accelerator producing protons with GeV energies and mA intensities, i.e. MW beam powers. Such beams can be used to produce very intense neutron fluxes in a spallation target, which can in turn yield very large quantities of fission fragments in a fission target. Proton beams with GeV energies and lower intensity – i.e. hundreds of μA – can also be used directly on a spallation target to produce (mostly) proton-rich nuclei. Thus by using a variety of targets, for neutron production, fission and spallation, this scheme can yield very large quantities of neutron-rich and proton-rich radioactive nuclei.

It was suggested by several people from the European RIB community that one should consider a heavy-ion accelerator as the preferred driver for EURISOL, on the basis of calculations which indicate enhanced yields for some (low-mass) radioactive ions, by using a variety of thick targets for in-flight production, followed by a solid ‘catcher’ for the ions produced and a subsequent ion source. However, since the recently-approved GSI upgrade will provide a high-mass, heavy-ion accelerator and an In-Flight facility, the Steering Committee is of the opinion that a relatively straightforward high-power proton driver accelerator, together with ISOL technique would provide a better overall solution for EURISOL. For this reason, a detailed study of a multi-beam (heavy-ion and proton) driver was not requested from the Driver Accelerator Task Group. However, the (non-negligible) cost implications of accelerating heavy ions with charge-to-mass ratios (q/A) of 1/2 and 1/3 were in fact also considered by that Task Group. Further, the post-accelerator studied for EURISOL also has the ability to accelerate beams of light masses for fragmentation purposes.

The radioactive nuclei produced by the driver beam must be extracted from the target as efficiently and as quickly as possible, then ionised by the ion source with high efficiency and in a high charge state, mass-selected and post-accelerated. The mass-selection system should at least separate the various radioactive nuclei produced in the target by their values of A, and possibly also separate the isobars. Three energy regions have been chosen for the post-accelerator:

1. **The first covers low-energy RIBs, i.e. tens of keV ('à la ISOLDE'), for experiments investigating ground-state properties, half-lives, decay modes, masses, electromagnetic moments, etc., and for Fundamental Interactions experiments.**
2. **Another region, up to about 10 A MeV, will allow experiments around the Coulomb barrier, for spectroscopic studies, high-spin investigation through fusion-evaporation reactions, etc.**
3. **The third region, up to 100 A MeV up to $A \approx 100$, will be devoted to fragmentation of very intense RIBs, study of the Equation Of State (EOS) of Nuclear Matter, etc.**

The experiments in these three energy regions will require a wide variety of scientific instrumentation, to study the ground-state properties, the various kinds of nuclear reactions, the different types of radiation produced, etc. These will include traps, multi-detector systems for charged particles, γ-rays and neutrons, as well as spectrometers, fragment separators, etc.

On the basis of these various options, the different Tasks Groups defined in section 1.4 have conducted their investigations, the results of which are described in detail in their respective Appendices to the EURISOL Report, and summarised below.

A possible plan of the proposed EURISOL facility is shown in figure 4.1. This is a schematic overall layout of the various parts of the EURISOL complex described above, i.e. the driver accelerator, the target/ion-source assembly, the mass-selection system and the post-accelerator, as well as the relative locations of some of the experimental areas. These elements will now be examined in more details.

4.2 Driver accelerator

As detailed in the report of the Driver Accelerator Task Group (Appendix B: '*The Driver Accelerator for EURISOL*'), the baseline option for the EURISOL driver is a 1-GeV, 5-mA, 5-MW, continuous-wave (CW) proton linac, which could later be extended to an energy of about 2 GeV if required. It includes the following three parts:

- **a low-energy section, up to 5 MeV, composed of a high-current proton source followed by a room-temperature radio-frequency-quadrupole (RFQ) accelerator;**
- **an intermediate-energy section, from 5 to 85 MeV, composed of a superconducting (SC) linac with independently phased cavities. An alternative solution, a drift-tube linac (DTL) at room temperature, has also been considered, with comparable investment costs but higher operating costs;**
- **a high-energy section, from 85 MeV to 1 or 2 GeV, composed of a SC linac with elliptical cavities.**

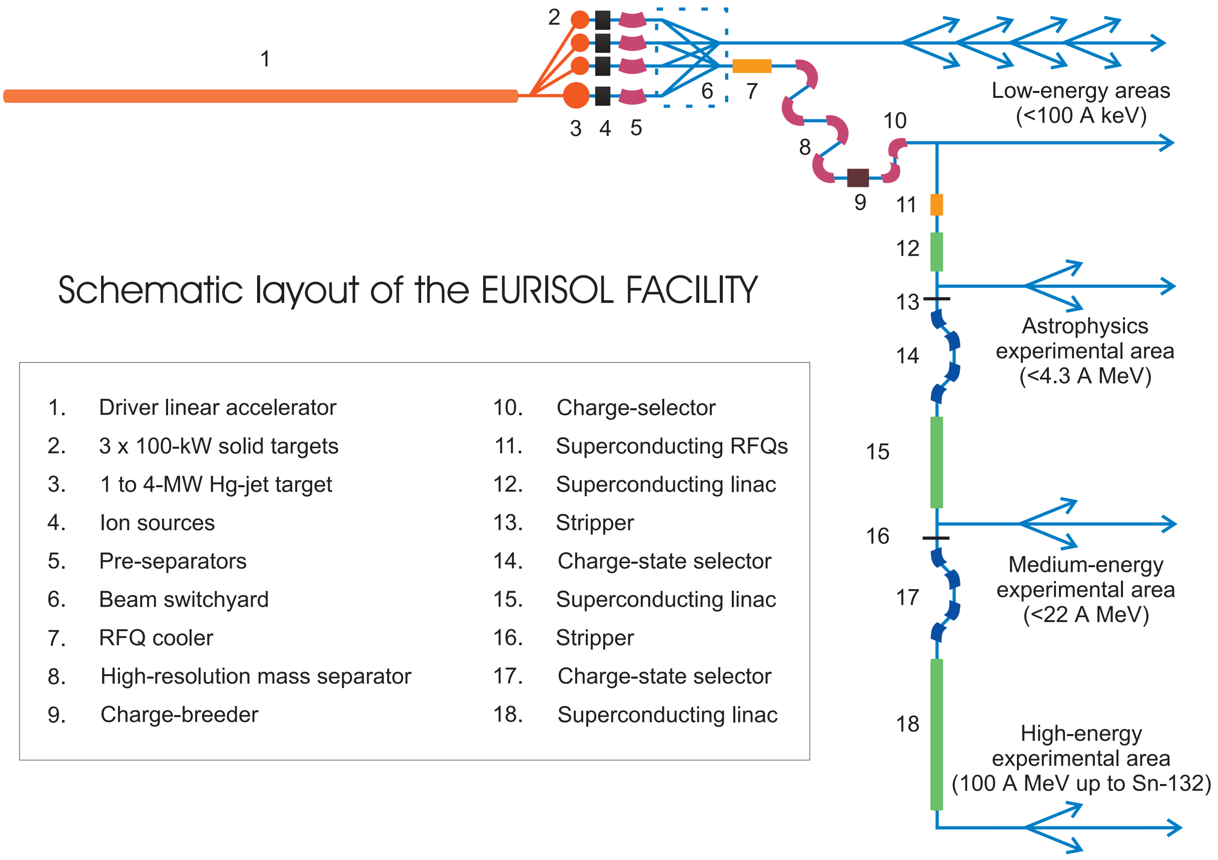


Fig. 4.1: Diagram showing a possible layout of the EURISOL facility. Details of the switchyard and other beamlines are represented very schematically.

The three sections of the driver accelerator are in different stages of advance with respect to the R&D necessary for their implementation.

The **low-energy section** is relatively straightforward since it can easily be extrapolated from projects presently under construction in Europe, mainly in France and Italy.

Concerning the **high-energy section** with elliptical cavities, it is to be noted that considerable progress has been made in their development. Indeed, they are also needed for high-power accelerator projects pertaining to other communities, independently of whether these require CW or pulsed beams. The former time structure is preferred for Accelerator Driven Systems (ADS) aiming at the transmutation of nuclear waste, whereas the latter is demanded by neutron spallation sources like the ESS and projects of the High-Energy Physics community, e.g. for a neutrino 'Super-Beam' facility. Although these other applications have to consider different optimisations for shaping their R&D programme, it should be possible to co-ordinate them with the planned EURISOL Design Study in order to avoid duplication of effort, where applicable.

The **intermediate-energy section** will use a rather new technology, i.e. independently-phased superconducting radio-frequency (SCRF) cavities of various types, which still need the outcome of important R&D efforts, recently launched by various laboratories in Europe. The potential applicability of this technology to projects of other communities should be also kept in mind.

Three further aspects of the baseline option have also been considered in detail:

- The 1-GeV linac can be upgraded in a straightforward way to an energy of 2 GeV, by increasing the number of SCRF cavities in the high-energy section, which would imply an increase of the investment costs. This possibility could be implemented at a latter stage, in order to increase the yields of some exotic nuclei produced in the target.
- The proton linac could accelerate other particles, i.e. deuterons, α-particles and heavy ions, with a mass-to-charge ratio $M/q = 2$, up to 500 A MeV and with similar electric beam currents as for proton operation, using a dedicated injector accelerator. This would also imply an increase of the investment costs, but could widen the panoply of exotic nuclei produced in the target.
- The CW mode of operation is preferable for a stand-alone driver accelerator. However, if the driver is to be shared in the context of a multipurpose facility with other scientific communities as mentioned above, then pulsed operation would be required, which is acceptable for EURISOL under certain conditions.

The R&D needed for the driver accelerator, and the possible synergies with other scientific communities, have also been investigated in detail; they will be summarised in section 7.

Finally, the option of using, as the driver, an electron accelerator, with an energy of 50 to 70 MeV and a beam current of 20 to 30 mA, has also been investigated. This scheme would produce large quantities of fission products in a uranium target, by photofission induced by the bremsstrahlung generated by the electron beam. The accelerator could be a SC electron linac, with an electron gun at about 100 keV, followed by a capture SC cavity up to about 5 MeV, and a SC section with SCRF cavities up to 50 to 70 MeV. Such a scheme would only produce neutron-rich fission fragments with a very asymmetric distribution, and would be competitive in price with the baseline option of a proton linac up to about 10^{15} fissions per second, but not beyond.

4.3 The target/ion-source assembly

In the report of the Target and Ion-Source Task Group, (see Appendix B: *'Targets & Ion Sources for EURISOL'*) the detailed description of the target stations is given, together with their ancillary laboratories for EURISOL. It is concluded that one can build a target laboratory with several target stations, which allows safe handling of the targets using the 1-GeV proton beams from the driver accelerator with tens of microamperes to milliamperes of intensity. With high reliability, this laboratory may provide a larger variety of low- and high-energy beams for more than 1200 8-hour shifts per year. These beams may be available simultaneously, or in a rapid time-sharing mode, with a projected intensity increase of a factor of up to 10^5 as compared to the presently available ISOL beams. This could be achieved via the following steps:

1. For EURISOL, new and much more efficient targets and ion sources can be developed by scaling, optimising and using proper engineering to utilise the large amount of know-how which already exists for the ISOL method.
2. To obtain the ultimate RIB intensity gain made possible by the proposed maximum available driver beam intensity (5-mA), a concept consisting of two targets is proposed, in order to prevent the severe thermal overload which would arise with a direct proton-irradiated production target. In this scenario, the proton beam is allowed to deposit a major fraction of its energy on a particularly well-cooled

primary target of high *Z*. The resulting intensity-amplified spectrum of fast spallation neutrons will then allow us to benefit from the particularly high formation cross-sections for production of fission fragments in a secondary U or Th fission ISOL target surrounding the primary target.

3. In addition, very large quantities of (mostly proton-rich) exotic nuclei can be produced by using a part of the proton beam intensity (less than about 100 μA) and sending it directly to a variety of ISOL targets.

Finally, by developing techniques for the production of some of the few elements missing on the list of presently available beams at ISOLDE, one will provide know-how which will most likely remove the present limitations of the ISOL method.

Accordingly, the Target and Ion-Source Task Group has investigated the following problems:

- the optimum conditions for producing neutrons by directing a high-energy projectile on a heavy spallation target;
- the energy deposition and secondary particle production in thick spallation targets;
- the design of a spallation neutron target able to withstand beam powers in the 5-MW range;
- the design of a fission target, optimised for the absorption of the neutron flux produced in the spallation target, and for the fast extraction of the fission products from the fission target;
- the design of a spallation target able to withstand beam powers of <100 kW by direct irradiation with a fraction of the available proton intensity, and for the fast extraction of the exotic nuclei thereby produced;
- the study of various ion sources and their coupling to the different targets;
- the study of targets for the production of a number of elements hitherto not available at ISOL facilities.

Furthermore the Task Group has investigated the following other aspects of the target stations:

- The R&D needed for the target and ion sources, and its possible synergies with other high-power target users have been identified and summarized.
- Various promising concepts using heavy ions as driver particles are discussed in their report, and the status of the European gas-catcher developments for stopping and extraction of low-energy heavy-ion fragments has been reviewed.
- A layout has been presented of the target areas and the ancillary laboratories, in which it is proposed to include 4 target stations, possibly built in a staged way. Since the targets, front ends, spent driver beam absorber, pre-separator magnet and target handling equipment are all proposed to be located below ground level, a total of 10 mass-separated low-energy ion beams may be allowed to emerge at the ground surface level. Of these, 3 originate from the switchyards of each of 3 low-intensity (100-kW) target stations, and one from a single high-intensity (<5-MW) target station. This allows a very high degree of flexibility in distributing the beams horizontally into 360 degrees, via a versatile and expandable beam distribution system, to the post accelerator and the experimental halls.

- Finally, we note that – as a spin-off – such a target laboratory offers a unique opportunity for the production of radioactive isotopes used for diagnosing and treating disease and for industrial purposes. Radioisotopes which are not currently available for medical and advanced research, but which offer the promise of new techniques and tools may be obtained as by-products from the proton-to-neutron converter target. Transfer of the ISOL target, ion-source and mass separation techniques to isotope production for medical diagnosis and treatment, will give to physicians access to radioisotopes with decay times, energy levels and purity better tailored to a patient's medical situation and safety requirements.

4.4 Mass-selection system and post-accelerator

As detailed in the report of the Post-Accelerator and Mass-Separator Task Group (Appendix D: *'Post-Accelerator & Mass-Separator for EURISOL'*), after a review of the low-energy separation techniques used for RIBs, an innovative separator based on the time-of-flight technique is proposed. It should have a mass resolving power of 10 000 and a large acceptance of 50π mm.mrad, for a beam extracted from the ion source at an energy of 30–60 keV: it should thus allow isobaric separation for a large number of RIBs, and have a large transmission, of the order of 50%. However, this concept is still to be proven experimentally, and its development needs R&D on one of its critical component, the radiofrequency chopper. An alternative would be a more conventional magnetic separator, using a number of dipole magnets with high-order field error-correction, using surface-mounted coils.

For the post-accelerator, various solutions have been studied in detail and compared: the cyclotron solutions, at room temperature (with 2 separated-sector cyclotrons) or superconducting (SC) (either a compact or a separated-sector SC cyclotron); the linac solution, superconducting, with high accelerating gradient cavities and multiple charge acceleration. The relative advantages and limitations of the various solutions are as follows:

- The cyclotron solutions are (probably) cheaper and allow separation of the accelerated beams. Some of them rely on existing technologies (the 2 room-temperature separated-sector cyclotrons), while others need more detailed studies (the SC cyclotrons). Their transmissions are however lower (10–15%, with a possible 50% for an SC separated-sector cyclotron), they do not allow multiple charge acceleration, and they generally require a separate accelerator for the lower energy region (up to 10 MeV/u).
- The linac solution is probably more expensive and does not allow full separation of the accelerated beams. It relies on existing technologies, but could benefit (in particular for its cost) from the development of new SC cavities. It has a high transmission (close to 50%), allows simultaneous acceleration of multiple charge states, does not require a separate accelerator for lower energies, and is easy to tune.

The Task Group has investigated other aspects of the mass-selection system and post-accelerator, in particular:

- the possibility of accelerating high-intensity beams (up to 300 μAe), if the post-accelerator were to be used as a possible driver. This could be realised within the SC linac solution;
- possible synergies with other major European installations or projects, such as the use of the present GANIL cyclotrons as a post-accelerator for EURISOL, and for the SC linac solution;

- the R&D needed for this part of EURISOL, for the cyclotron solutions (mostly for the SC cyclotrons), for the linac solution (development of SC cavities) and for the mass-separation system.

4.5 Instrumentation

The Task Group on scientific instrumentation (detector system, etc) to be installed at the planned EURISOL facility has examined the following topics :

- techniques needed for studying the ground-state properties of exotic nuclei, including their masses, electromagnetic moments, their matter and charge radii, and observables related to fundamental interactions and symmetries;
- instrumentation required for nuclear structure studies: in-beam γ-ray and conversion electron spectroscopy, decay spectroscopy for tagging purposes, and β-delayed neutron spectroscopy;
- development of γ-ray tracking techniques, detectors, digital signal-processing, pulse-shape analysis, and tracking algorithms;
- instrumentation for reaction studies with RIBs, i.e. arrays of multidetectors for light charged particles, γ-rays, heavy fragments, neutrons and fission fragments, and target and beam requirements;
- spectrometers for ions and charged particles: gas-filled separators, recoil mass spectrometers, ray-tracing spectrometers and fragment recoil-separators;
- a special technique, which could make use of intense RIBs, muon and antiproton beams if these were available on the same site;
- the electronic and data acquisition systems to be associated with EURISOL.

The Instrumentation Task Group has also made cost estimates for some of the main instruments to be placed in the experimental area, and identified R&D projects to be carried out during the next phase of the EURISOL programme.

4.6 A possible layout of the EURISOL facility

As a first approach, the Target and Ion-Source Task Group have suggested a possible arrangement for three 100-kW targets and one 5-MW target, below ground level, to feed RIBs to a number of different experimental areas, as well as to the mass-separator and subsequent post-accelerator. This is shown in a three dimensional drawing of figure 4.2 below.

Figure 4.3 shows a side-view of one possible layout, with several different levels.

A layout of the complete EURISOL facility, with a 1-GeV proton driver accelerator, target and ion-source areas, beam switchyard, mass-separator, 100 A-MeV post-accelerator linac and experimental areas, is shown in figure 4.4. The precise layout will of course depend very much on the site chosen for the project.

The various Working Groups set up in this Task have also prepared possible layouts of the different EURISOL experimental areas, which are depicted schematically in figures 4.5 to 4.8.

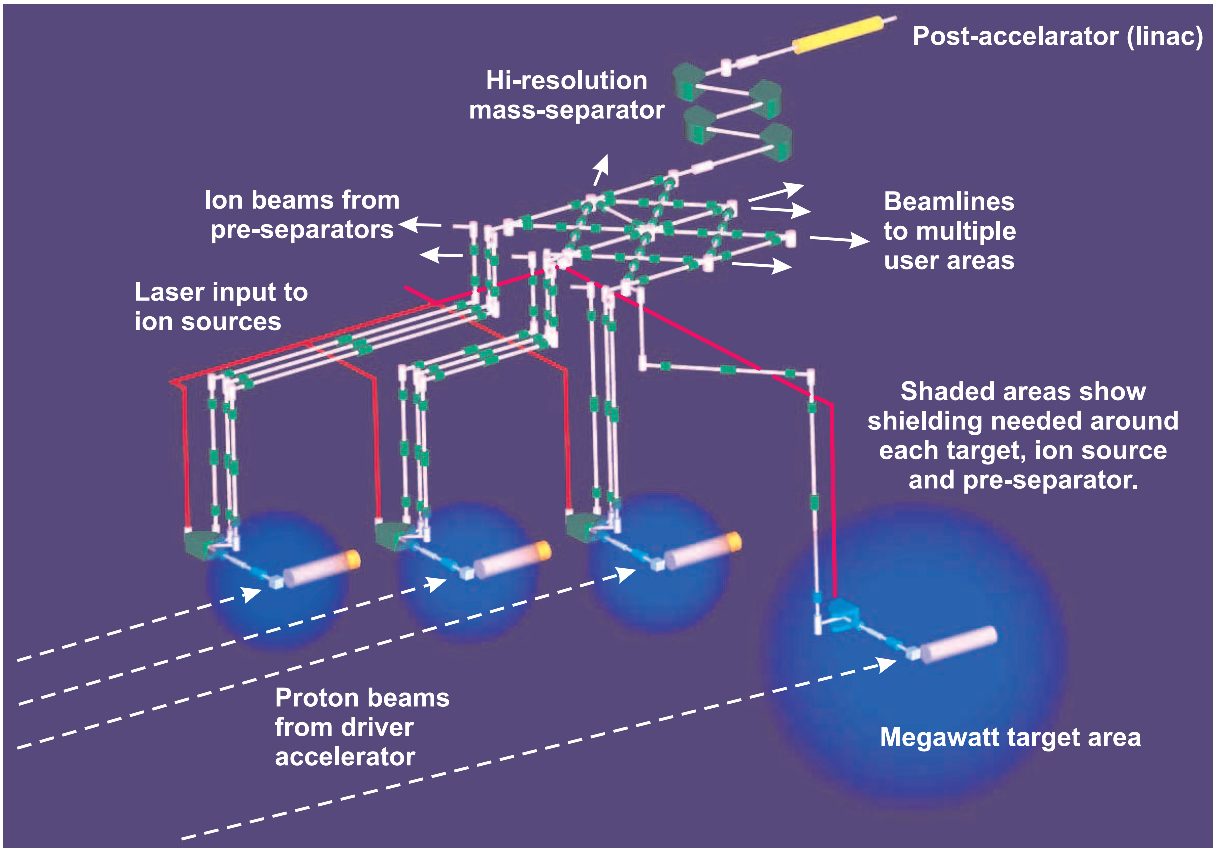


Fig. 4.2: A schematic diagram showing a possible layout of three 100-kW targets and one MW target. Each of the four targets is shown equipped with a laser-ionisation ion source. Each ion source would feed a low-resolution mass-separator, from which several beams could be routed to various experimental areas, or to a high-resolution mass-separator feeding the post-accelerator.

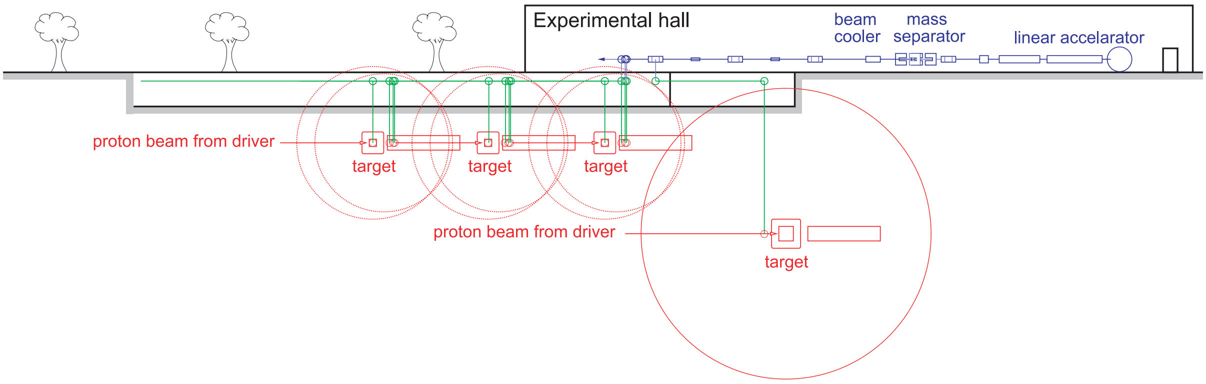


Fig. 4.3: Side elevation of the schematic shown above. Lower levels provide for the driver beams, beam dumps, targets, ion sources and pre-separators, while the upper levels would contain the beam switchyard, mass-separator and post-accelerator. The red circles indicate the volume of (typically rock or concrete) shielding needed around the respective targets. The use of steel could decrease the volume needed for the high-power target, for example.

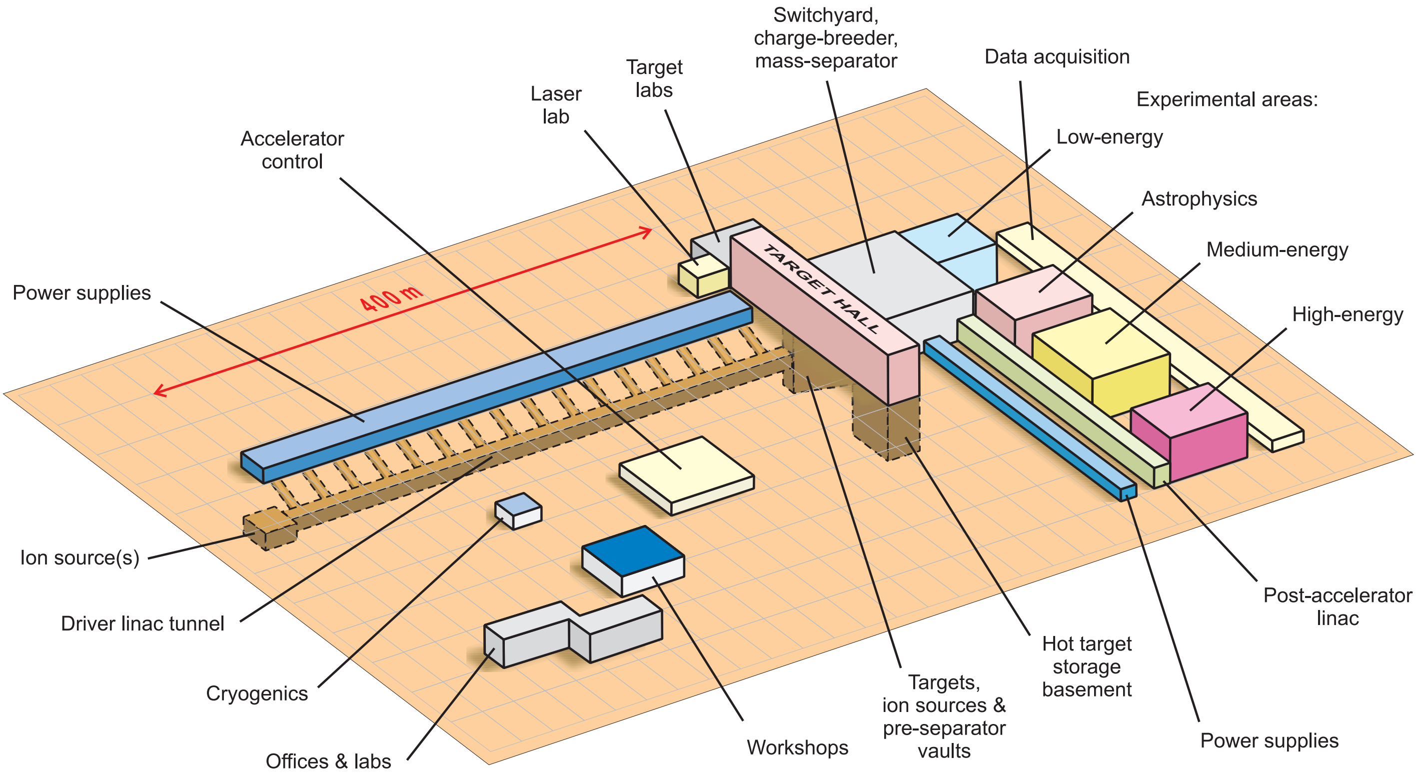


Fig 4.4: Schematic drawing showing a possible layout of the EURISOL facility. Details of each of the experimental areas are shown in the figures below.

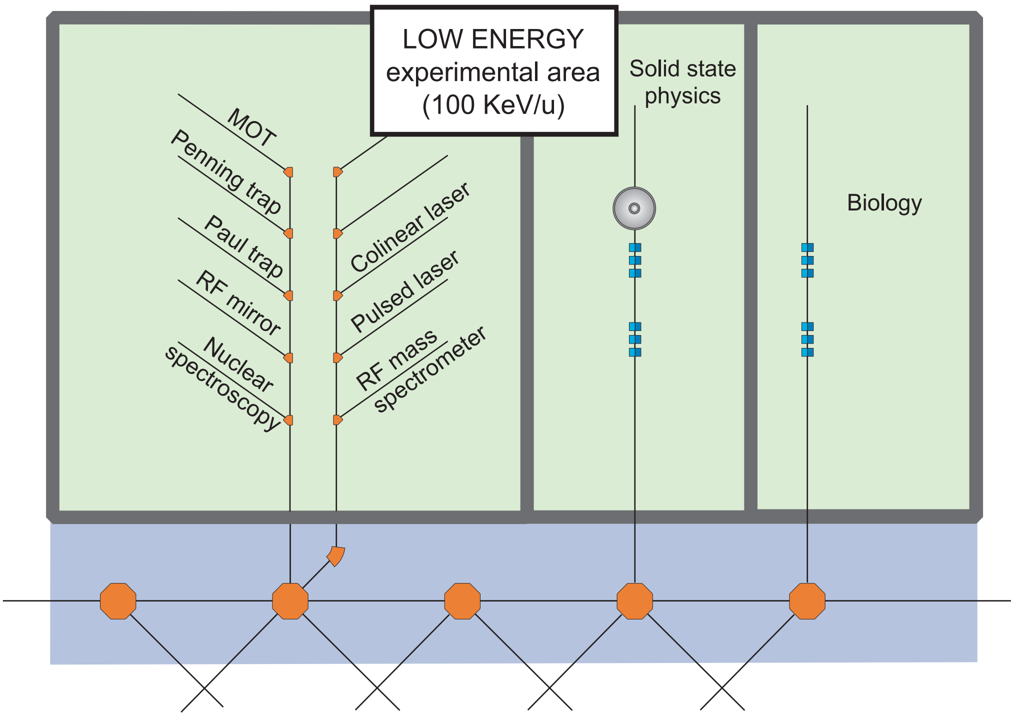


Fig 4.5: The low-energy experimental area

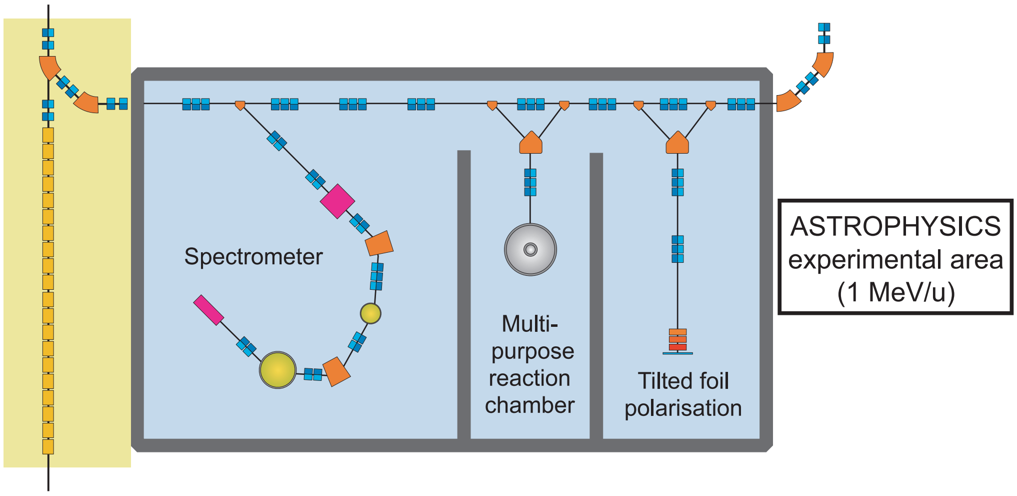


Fig 4.6: The Astrophysics experimental area

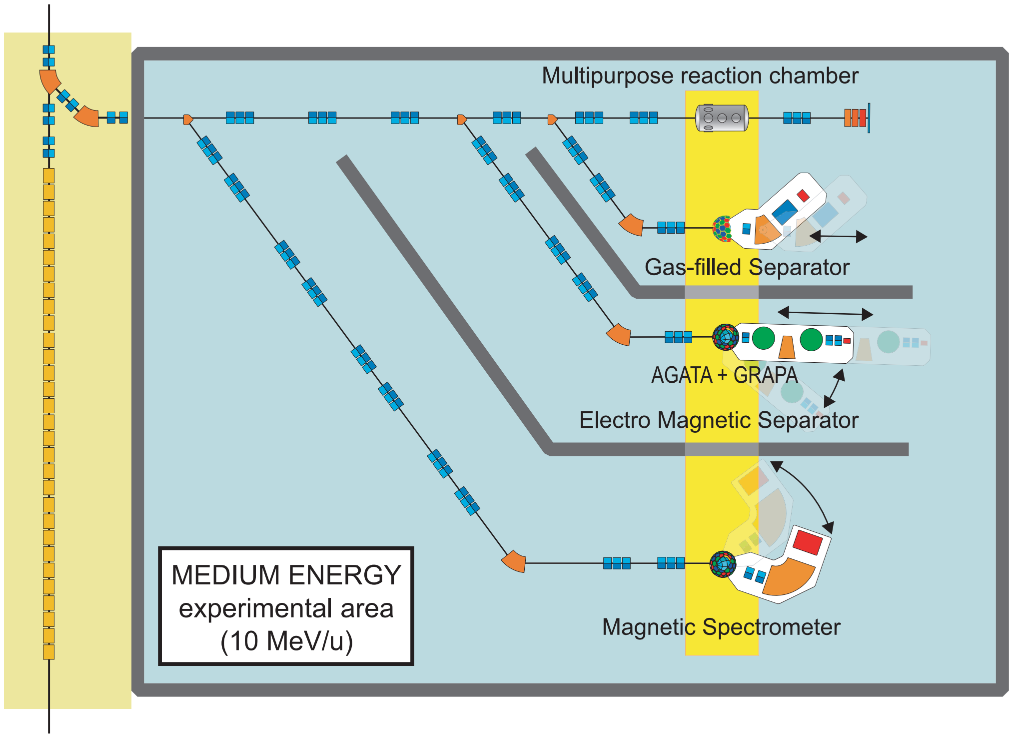


Fig 4.7: The medium-energy experimental area

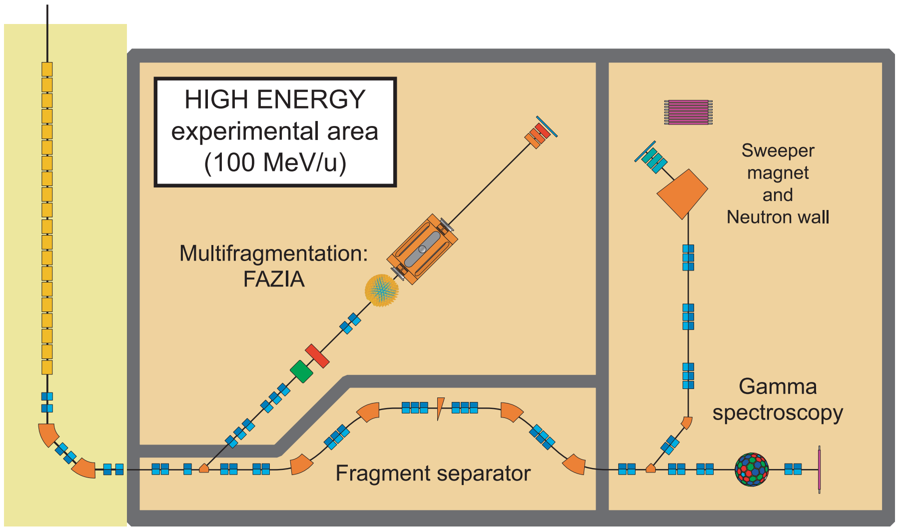


Fig 4.8: The high-energy experimental area

5 Expected performance of EURISOL

5.1 Nuclides produced by direct or indirect irradiation

Presented in the Report of the Target and Ion-Source Task Group (see Appendix C) is a study of the production rates of exotic nuclei in the targets and the power deposition of the driver particles in the target material.

By analysing and testing various codes for calculation of production cross sections for formation of the nuclides of interest produced by **direct impingement of protons** on a variety of targets, the **ABRABLA code** developed at GSI was found to be best suited to our purpose. It confirmed and quantified that proton-induced spallation, fragmentation and fission reactions provide the most cost-effective production method for coverage of all regions of the chart of nuclides.

Calculations of the power deposition in the target materials and measurements of the heat dissipation indicated **a technological limit at <100kW** absorbed power. In order to obtain the RIB intensity increase allowed by the highest driver beam intensities, in the more restricted region of fission fragments, it is necessary to make use the so-called **'converter' method**. In this case the primary proton beam is converted into a high flux of spallation neutrons, with the converter target surrounded by a secondary fission target. The fission yields induced and amplified by the spectrum of spallation neutrons were found to be best calculated using the **MCNPX code**.

The calculations of the production rates in the targets were followed up by a comparison with the production rates and beam intensities measured at ISOLDE. In order to reduce the beam time and manpower resources needed for this task, only a limited but representative range of elements, suggested by NuPECC and the Key Experiments Task Group (viz. Be, Ar, Ni, Ga, Kr, Sn and Fr), were treated in depth.

Firstly, the measurement and detailed evaluation of a large number of engineering parameters of presently operating targets and ion sources for the chosen set of benchmark elements were done at ISOLDE. Secondly a number of calculation codes and techniques were developed that make use of these parameters for converting the measured beam intensities back into production rates in the targets, as described in Appendix C: *'Targets & Ion-Sources for EURISOL'*.

As shown in section 2 of that Appendix, the production yields calculated from the cross sections and those derived from the ISOLDE RIB measurements show quite satisfactory agreement. The combined uncertainties in the ratio of the production rate measurements and those calculated from the formation cross sections are estimated to be within less than a factor of 2 near stability, rising to an uncertainty factor of 5–50 far from stability. It was evident that an improvement of this situation would need a major experimental effort, considered to be outside the scope of this report.

5.2 Expected intensities of the RIBs

The projected final accelerated RIB intensities of the isotopes of the benchmark elements Be, Ar, Ni, Ga, Kr, Sn, Fr are shown in column N of the tables 5.1 and 5.2 below for the two scenarios, i.e. direct and indirect irradiation, respectively.

Since the uncertainties in the experimental yields measured at ISOLDE (listed in column E of tables 2.1 and 2.2) are only a factor of 1 near stability rising to a factor of 5 far from stability, they were used to calculate the intensity improvement factor for EURISOL.

Firstly, we assumed that the necessary modifications to the target geometries will have been made in order to adapt to the state of the art and optimise the production and fast release of the short-lived species. The decay losses were then calculated by using the new Monte Carlo code described in Section 2.5.2 of Appendix C. In addition, the ionisation efficiency of the ion source best suited for each element was chosen. Finally, the decay-corrected charge-breeding efficiency and the post-acceleration efficiency were applied using the parameters from REX-ISOLDE given in table 2.4 of Appendix C. The 'EURISOL gain factor' quoted in Appendix C is the ratio of the projected intensities to the best presently-available RIB intensities of the reference elements produced at ISOLDE with the maximum available proton beam intensity of 2 µA.

The resulting improvement that should be achieved EURISOL can be seen from column N of tables 5.1 and 5.2 below. It can be seen that the intensities expected at EURISOL may be from 100 to 100 000 times higher, depending on the element, the isotope and the irradiation method. Similar gains are expected for the more than 600 other RIBs produced at ISOLDE and listed in its database [9]. The uncertainties in these final beam intensities are estimated to be a factor of 5 to 25, where the additional factor of 5 above the uncertainty of the ISOLDE measurements will depend on the degree of success in developing the high-power aspects of the targets.

Table 5.1: Present and projected accelerated RIB intensities for the elements suggested by the Key Experiments Task Group and NuPECC (i.e. Be, Ar, Ni, Ga, Kr, Sn, and Fr) for a direct 100-µA proton beam.

On-line data from CERN/ISOLDE						**Predicted for a 100-kW target staton**
Target and ion source	**Ion**	**Mass no. (*A*)**	**Half-life**	**Measured yield [ions/µC]**	**In-target yield [atoms/µC]**	**Post-accelerated RIB intensity [ions/s]**
A	B	C	D	E	F	N
Ta	**Be**	**10**	1.51E6 a	4.9E+08	6.1E+09	**1.6E+11**
direct		**11**	13.81 s	3.4E+06	5.2E+07	**1.1E+09**
RILIS		**12**	21.5 ms	4.8E+04	8.3E+07	**1.0E+06**
		14	4.35 ms	6.1E+00	1.8E+05	**1.3E+02**
Ta	**Be**	**12**	21.5 ms	5.00E+06	8.67E+09	**2.89E+07**
		14	4.35 ms	3.40E+01	1.01E+06	**1.23E+00**
Graphite	**Be**	**7**	53.12 d	1.9E+12/s	(off-line)	**1.9E+12**
off-line RILIS		**10**	1.51E6 a	1.9E+12/s	(off-line)	**4.1E+12**
CaO	**Ar**	**31**	15.1 ms	1.5E+00	3.7E+03	**1.2E+01**
direct		**32**	98 ms	3.3E+03	8.2E+06	**2.3E+05**
MK7		**33**	173 ms	3.8E+04	5.4E+06	**3.7E+06**
		34	844 ms	1.7E+06	4.2E+09	**1.7E+08**
		35	1.775 s	4.3E+07	1.9E+09	**4.6E+09**

On-line data from CERN/ISOLDE						Predicted for a 100-kW target staton
Target and ion source	**Ion**	**Mass no. (*A*)**	**Half-life**	**Measured yield [ions/µC]**	**In-target yield [atoms/µC]**	**Post-accelerated RIB intensity [ions/s]**
A	B	C	D	E	F	N
UC$_x$	**Ar**	**35**	1.775s	6.5E+02	4.5E+04	**1.2E+05**
direct		**41**	109.34 m	1.4E+07	6.8E+08	**3.4E+09**
MK7		**43**	5.37 m	4.5E+06	2.2E+08	**1.1E+09**
		44	11.87 m	3.0E+06	1.5E+08	**7.3E+08**
		49	135 ms	1.0E+01	2.5E+03	**1.4E+03**
		50	85 ms	2.5E-01	1.0E+02	**2.4E+01**
UC$_x$	**Ni**	**56**	5.9 d	2.0E+03	3.3E+04	**8.5E+04**
direct		**59**	8E3 a	6.0E+06	1.0E+08	**2.6E+08**
RILIS		**65**	2.5 h	7.0E+07	1.2E+09	**3.0E+09**
		66	55 h	1.0E+08	1.7E+09	**4.3E+09**
		67	21 s	7.0E+05	7.0E+07	**2.0E+07**
		68	29 s	4.0E+05	3.1E+07	**1.1E+07**
	69g	**69**	11.2 s	2.0E+04	3.6E+06	**5.7E+05**
	69m	**69**	3.5 s	<2.0E3	<1.2E+06	**<5.7E+04**
		70	6.0 s	~1.0E4	3.4E+06	**~2.8E+05**
		71	2.56 s	<2.0E3	<1.8E+06	**<5.7E+04**
		74	0.9 s	<200	<7.8E+05	**<5.7E+03**
		76	0.24 s	<10	<3.6E+05	**<2.8E+02**
ZrO$_2$	**Ga**	**61**	0.15 s	1.0E+01	7.6E+02	**8.5E+01**
direct		**62**	116.1 ms	4.0E+03	4.3E+05	**3.4E+04**
RILIS		**63**	32.4 s	1.2E+06	7.8E+06	**2.6E+07**
		64	2.627 m	1.5E+07	8.0E+07	**3.2E+08**
		65	15.2 m	9.5E+07	4.8E+08	**2.0E+09**
		66	9.49 h	2.0E+08	1.0E+09	**4.3E+09**
		67	3.2612 d	2.6E+08	1.3E+09	**5.5E+09**
		68	67.629 m	3.1E+08	1.6E+09	**6.6E+09**
		70	21.14 m	8.0E+07	4.0E+08	**1.7E+09**
		72	14.10 h	1.0E+07	5.0E+07	**2.1E+08**
		73	4.86 h	3.7E+06	1.9E+07	**7.9E+07**
		74	8.12 m	7.60E+05	3.9E+06	**1.6E+07**
		75	126 s	1.1E+05	6.0E+05	**2.3E+06**
UC$_x$	**Ga**	**64**	2.627 m	1.0E+04	1.4E+06	**3.6E+06**
direct surface ionisation		**68**	67.629 m	9.0E+06	1.3E+09	**3.3E+09**
		70	21.14 m	2.5E+07	3.6E+09	**9.1E+09**
		74	8.12 m	2.8E+07	4.0E+09	**1.0E+10**
		75	126 s	2.1E+07	3.0E+09	**7.7E+09**
		76	32.6 s	1.3E+07	2.0E+09	**3.2E+09**
		77	13.2 s	7.7E+06	1.2E+09	**1.9E+09**
		78	5.09 s	3.9E+06	7.1E+08	**9.5E+08**
		79	2.847 s	2.6E+06	5.4E+08	**6.3E+08**
		80	1.697 s	3.5E+05	8.6E+07	**8.5E+07**
ZrO$_2$-177	**Kr**	**72**	17.2 s	1.0E+03	5.5E+04	**1.1E+05**
direct		**73**	27.0 s	2.7E+04	1.3E+06	**2.9E+06**
MK7		**74**	11.5 m	5.5E+05	1.8E+07	**1.5E+08**

On-line data from CERN/ISOLDE						Predicted for a 100-kW target staton
Target and ion source	**Ion**	**Mass no. (*A*)**	**Half-life**	**Measured yield [ions/µC]**	**In-target yield [atoms/µC]**	**Post-accelerated RIB intensity [ions/s]**
A	B	C	D	E	F	N
ZrO_2-177	**Kr**	**75**	4.3 m	5.5E+06	1.9E+08	**1.5E+09**
direct		**77**	74.4 m	9.6E+07	3.2E+09	**2.6E+10**
MK7	79m	**79**	50 s	6.4E+07	2.6E+09	**1.7E+10**
		87	76.3 m	5.0E+05	1.7E+07	**1.3E+08**
Nb-088	**Kr**	**69**	32 ms	1.5E-04	2.6E+00	**8.0E-03**
direct		**70**	57 ms	1.5E-02	1.1E+02	**1.2E+00**
MK7		**71**	97 ms	8.5E-01	2.8E+03	**9.5E+01**
		72	17.2 s	3.7E+03	2.5E+05	**5.3E+05**
		73	27.0 s	2.2E+05	1.2E+07	**3.0E+07**
	79m	**79**	50 s	7.8E+08	3.6E+10	**1.1E+11**
				(Assumed 3% ionisation efficiency)		
UC	**Kr**	**75**	4.3 m	7.0E+04	1.5E+06	**7.8E+06**
direct		**77**	74.4 m	2.7E+06	5.9E+07	**3.0E+08**
MK7		**87**	76.3 m	2.1E+08	4.6E+09	**2.4E+10**
		88	2.84 h	1.8E+08	3.9E+09	**2.0E+10**
		89	3.15 m	2.7E+08	6.1E+09	**3.1E+10**
		90	32.32 s	2.5E+08	5.9E+09	**2.8E+10**
		91	8.57 s	1.9E+08	5.2E+09	**2.0E+10**
		92	1.84 s	1.1E+08	4.8E+09	**8.9E+09**
		93	1.286 s	3.7E+07	2.0E+09	**3.0E+09**
		94	212 ms	3.5E+06	7.2E+08	**2.4E+08**
		95	114 ms	3.6E+05	1.4E+08	**2.3E+07**
		96	80 ms	6.8E+04	2.5E+07	**2.9E+06**
		97	63 ms	7.2E+03	2.5E+06	**2.7E+05**
		98	46 ms	5.2E+02	2.5E+05	**1.5E+04**
		99	40 ms	1.0E+01	6.3E+03	**2.6E+02**
ThC	**Kr**	**75**	4.3 m	3.0E+04	1.2E+06	**3.4E+06**
direct		**77**	74.4 m	1.7E+06	6.8E+07	**1.9E+08**
MK7		**79**	50 s	1.6E+07	6.8E+08	**1.8E+09**
	81m	**81**	13.10 s	4.4E+06	2.0E+08	**3.3E+08**
		88	2.84 h	4.4E+08	1.8E+10	**5.0E+10**
		89	3.15 m	6.7E+08	2.7E+10	**7.5E+10**
		90	32.32 s	5.1E+08	2.2E+10	**5.7E+10**
		91	8.57 s	3.9E+08	1.9E+10	**2.9E+10**
		92	1.84 s	1.3E+08	1.0E+10	**9.7E+09**
		93	1.286 s	3.6E+07	3.6E+09	**2.7E+09**
		95	114 ms	2.2E+05	2.2E+08	**1.4E+07**
UC	**Sn**	**106**	115 s	1.4E+03	1.5E+04	**3.2E+04**
direct		**107**	2.90 m	5.0E+04	5.3E+05	**1.2E+06**
RILIS		**108**	10.30 m	3.2E+05	3.2E+06	**8.1E+06**
		109	18.0 m	3.2E+06	3.2E+07	**8.1E+07**
		110	4.11 h	1.3E+07	1.3E+08	**3.3E+08**
		111	35.3 m	4.0E+07	4.0E+08	**1.0E+09**
	113m	**113**	21.4 m	1.9E+08	1.9E+09	**4.8E+09**

On-line data from CERN/ISOLDE						Predicted for a 100-kW target staton
Target and ion source	**Ion**	**Mass no. (*A*)**	**Half-life**	**Measured yield [ions/µC]**	**In-target yield [atoms/µC]**	**Post-accelerated RIB intensity [ions/s]**
A	B	C	D	E	F	N
UC (Also 6.9 m isomer) (Also 1.7 m isomer) (Also 58.4 s isomer)	128m	**128**	6.5 s	2.1E+08	4.3E+09	**3.5E+09**
	129m	**129**	2.23 m	2.2E+08	2.4E+09	**4.9E+09**
	130m	**130**	3.72 m	2.2E+08	2.3E+09	**5.3E+09**
	131m	**131**	56.0 s	2.8E+08	3.2E+09	**5.6E+09**
		132	39.7 s	2.0E+08	2.4E+09	**4.0E+09**
		133	1.45 s	1.5E+07	8.4E+08	**2.5E+08**
		134	1.12 s	2.1E+06	1.5E+08	**3.5E+07**
UC direct surface ionisation	**Fr**	**202**	0.34 s	1.4E+04	2.3E+05	**4.9E+04**
		203	0.55 s	5.6E+04	5.9E+05	**1.9E+05**
		205	3.85 s	1.1E+07	4.3E+07	**4.5E+07**
		206	15.9 s	9.8E+07	2.5E+08	**4.3E+08**
		207	14.8 s	1.8E+08	4.8E+08	**8.0E+08**
		209	50 s	6.7E+08	1.5E+09	**2.9E+09**
		211	3.1 min	1.4E+09	2.9E+09	**6.8E+09**
		213	34.6 s	1.3E+09	3.0E+09	**5.9E+09**
		220	27.4 s	2.4E+08	5.7E+08	**1.1E+09**
		223	21.8 min	1.6E+07	3.3E+07	**8.3E+07**
		224	3.3 min	1.1E+07	2.3E+07	**5.4E+07**
UC direct surface ionisation	**Fr**	**225**	4.0 min	6.9E+06	1.4E+07	**3.4E+07**
		226	48 s	3.1E+06	6.9E+06	**1.4E+07**
		227	2.47 min	2.2E+06	4.5E+06	**1.1E+07**
		228	39 s	6.0E+05	1.4E+06	**2.7E+06**
		230	19.1 s	6.9E+04	1.7E+05	**3.1E+05**
		232	5 s	3.1E+03	1.1E+04	**1.3E+04**
ThC direct surface ionisation	**Fr**	**203**	0.55 s	2.1E+04	5.1E+05	**7.2E+04**
		205	3.85 s	6.9E+06	3.5E+07	**2.3E+07**
		207	14.8 s	2.2E+08	6.2E+08	**7.6E+08**
		209	50 s	1.2E+09	2.8E+09	**5.1E+09**
		211	3.1 min	2.7E+09	5.5E+09	**1.3E+10**
		213	34.6 s	3.7E+09	8.6E+09	**1.5E+10**
		220	27.4 s	3.1E+09	7.5E+09	**1.1E+10**
		223	21.8 min	3.2E+08	6.3E+08	**1.6E+09**
		224	3.3 min	2.5E+08	5.1E+08	**1.2E+09**
		225	4.0 min	2.0E+08	4.1E+08	**9.7E+08**
		226	48 s	6.6E+07	1.5E+08	**2.7E+08**
		227	2.47 min	6.0E+07	1.2E+08	**2.8E+08**
		228	39 s	1.1E+07	2.4E+07	**4.2E+07**

Table 2.2: Present and projected accelerated RIB intensities for some fission products (i.e. Ni, Ga, Kr, and Sn), for a 4-mA proton beam on a 'converter' spallation source surrounded by an actinide target.

On-line data from CERN/ISOLDE						Predicted for a 4-MW target station
Target & ion source	**Ion**	**Mass no. (*A*)**	**Half-life**	**Measured yield [ions/µC]**	**In-target yield [atoms/µC]**	**Post-accelerated RIB intensity [ions/s]**
A	B	C	D	E	F	N
				simulated	*simulated*	
UC	**Ni**	**66**	55 h	*1.0E+03*	*1.0E+03*	**3.8E+07**
+ converter		**67**	21 s	*1.4E+03*	*8.2E+03*	**1.5E+06**
RILIS		**68**	29 s	*2.3E+03*	*1.1E+04*	**3.0E+06**
	69g	**69**	11.2 s	*1.2E+03*	*1.3E+04*	**1.1E+06**
		70	6.0 s	*7.3E+02*	*1.5E+04*	**5.0E+05**
		71	2.56 s	*2.4E+02*	*1.3E+04*	**1.3E+05**
		74	0.9 s	*3.1E+01*	*7.3E+03*	**1.4E+04**
		76	0.24 s	*3.8E-01*	*6.7E+02*	**1.7E+02**
UC	**Ga ****	**70**	21.14 m	1.3E+05	6.5E+05	**>1.5E+09**
+ converter		**73**	4.86 h	4.8E+05	2.4E+06	**>5.5E+09**
RILIS		**74**	8.12 m	5.2E+05	2.6E+06	**>5.5E+09**
		75	126 s	8.3E+05	4.2E+06	**>7.4E+09**
		76	32.6 s	7.0E+05	3.6E+06	**>3.8E+09**
		77	13.2 s	7.6E+05	4.2E+06	**>2.3E+09**
		78	5.09 s	5.5E+05	3.4E+06	**>8.1E+08**
		79	2.847 s	6.5E+05	4.6E+06	**>7.6E+08**
		80	1.697 s	3.1E+05	2.6E+06	**>1.6E+08**
		81	1.217 s	1.9E+05	1.8E+06	**>9.8E+07**
		82	0.599 s	3.6E+04	5.1E+05	**>1.2E+07**
		83	0.31 s	1.0E+04	2.3E+05	**>2.2E+06**
		84	85 ms	8.0E+01	6.0E+03	**>4.6E+03**
Assumed T1/2=50ms		**85**	unknown	1.2E+01	1.6E+03	**>2.9E+02**
Assumed T1/2=30ms		**86**	unknown	1.5E+00	3.6E+02	**>7.5E+00**
UC	**Kr**	**87**	76.3 m	1.1E+07	2.4E+08	**1.1E+12**
+ converter		**88**	2.84 h	2.2E+07	5.0E+08	**2.6E+12**
MK7		**89**	3.15 m	3.8E+07	8.9E+08	**4.3E+12**
		90	32.32 s	5.5E+07	1.3E+09	**4.7E+12**
		91	8.57 s	4.9E+07	1.4E+09	**2.7E+12**
		92	1.84 s	3.2E+07	1.3E+09	**7.4E+11**
		93	1.286 s	1.1E+07	5.0E+08	**2.0E+11**
		94	212 ms	1.2E+06	1.8E+08	**5.7E+09**
		95	114 ms	1.2E+05	3.6E+07	**3.3E+08**
UC_x	**Sn**	**109**	18.0 m	1.4E+04	1.4E+05	**3.1E+08**
+ converter		**110**	4.11 h	1.4E+04	1.4E+05	**3.2E+08**
RILIS		**111**	35.3 m	2.4E+05	2.5E+06	**5.6E+09**
		113	21.4 m	1.1E+06	1.1E+07	**2.5E+10**
	117m	**117**	13.60 d	2.0E+07	2.0E+08	**4.6E+11**
	119m	**119**	293.1 d	2.6E+07	2.6E+08	**6.0E+11**
	123m	**123**	40.06 m	4.6E+07	4.6E+08	**1.1E+12**
	125m	**125**	9.52 m	6.9E+07	7.0E+08	**1.2E+12**
	127m	**127**	4.13 m	6.3E+07	6.6E+08	**8.8E+11**
	128m	**128**	6.5 s	4.4E+07	9.1E+08	**5.7E+10**

On-line data from CERN/ISOLDE						Predicted for a 4-MW target station
Target & ion source	**Ion**	**Mass no. (*A*)**	**Half-life**	**Measured yield [ions/µC]**	**In-target yield [atoms/µC]**	**Post-accelerated RIB intensity [ions/s]**
A	B	C	D	E	F	N
(Also 6.9 m isomer)	129m	**129**	2.23 m	6.4E+07	6.9E+08	**5.2E+11**
(Also 1.7 m isomer)	130m	**130**	3.72 m	1.2E+08	1.2E+09	**1.2E+12**
(Also 58.4 s isomer)	131m	**131**	56.0 s	2.8E+08	3.2E+09	**1.6E+12**
		132	39.7 s	2.0E+08	2.4E+09	**9.3E+11**
		133	1.45 s	9.5E+07	5.5E+09	**5.6E+10**
		134	1.12 s	1.2E+07	8.3E+08	**5.9E+09**
		135	530 ms	1.0E+05	1.5E+07	**3.6E+07**
		136	250 ms	3.0E+03	1.0E+06	**6.8E+05**
		137	190 ms	1.0E+02	4.7E+04	**1.9E+04**
Assumed $T_{1/2}$=100ms		**138**	unknown	2.0E+00	2.2E+03	**1.9E+02**

*** Note: measured yields for Ga are lower limits, owing to a Ta-converter which was partly twisted during the measurements.*

5.3 Comparison between ISOL and in-flight yields

The only European facility to which EURISOL can be compared is the new GSI heavy-ion fragmentation project. In their conceptual design report [5] they present calculated rates of all nuclides with expected half-lives down to 100 ns. These include those of the elements proposed by NuPECC [2] as benchmarks for prediction of ion-beam rates in new facilities and for comparison of projects. In this report (for the reasons given below) we presents only the beam intensities of these NuPECC elements extrapolated to EURISOL conditions but they are based on actual measurements of the individual beams and all other relevant parameters.

In principle this allows a comparison of the beam intensities of the two facilities. However, this is not an easy task and one should note the following important differences of these fully complementary projects.

The GSI projectile fragmentation method yields very high energy beams of poor emittance for which the intensities are independent of the chemical properties and largely also of half-life. This allows a free choice of target and projectile for optimal production of beams of all elements. Only the knowledge of the formation cross-section is needed to predict all the intensities.

Figure 5.1 shows the predicted rates of the reference elements at the future GSI [5] of stable and unstable projectile fragments emerging in direction of the fragment separator from an optimised graphite target irradiated by 10^{12} ions/s, of the most favourable beam with an energy of 1 GeV/u. They were all calculated using various models for cross section prediction [5]. It should be noted that although these models were extensively compared to a large database of measured production cross-sections of nuclei close to stability only [10], beam intensities are given for an impressive number of unknown – or even unbound – species very far from stability where no model has been tested against experiment.

The EURISOL method of thick target fragmentation has the highest production rates yielding extremely high beam intensities of excellent emittance, allowing loss-free energy variability. A dependence on the chemical properties of the elements requires individually developed targets for almost each element and results in half-life-dependent losses of the shortest-lived nuclei. The refractory target materials needed have at present only been developed and tested for 70 of the 92 elements, many of which still leave room for optimisation. Prediction of the beam intensities therefore requires, in addition to the yields or the formation cross-sections, elaborate measurements of a number of target and ion-source parameters, that, together with new codes, allow scaling the decay losses to the larger-volume EURISOL targets. This was done for the first time for this report [11] so that proper comparisons can be made for beams of the NuPECC reference elements.

Figure 5.1 shows the expected intensities at EURISOL of the 60-keV stable and unstable mass-separated beams injected into the charge-breeder of the post-accelerator. Data are only given for beams for which half-lives, intensities, and target and ion-source parameters have actually been measured, so that reliable and conservative extrapolation to the higher driver beam intensity at EURISOL can be made, as is discussed at length in reference [11]. The uncertainties in the intensities are estimated to be a factor of two near stability, rising to a factor of 5 far from stability.

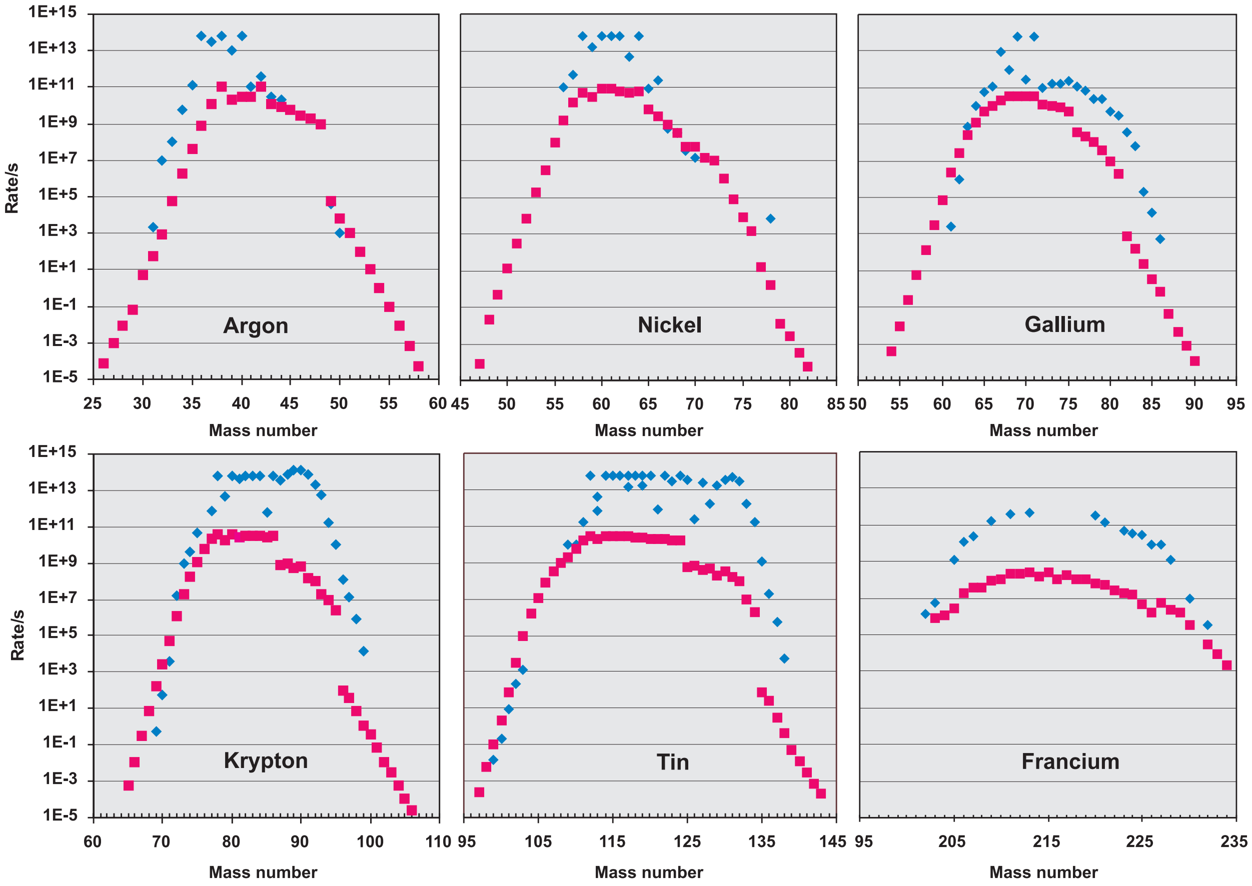


Fig. 5.1: Predicted rates of isotopes of a representative sample of elements. (Blue): Produced at EURISOL from the most favourable target station, before injection into the charge-breeder and post-accelerator. (Red): Produced at the future GSI facility, emerging in direction of the fragment separator from an optimised graphite target irradiated by 10^{12} ions/s, of the most favourable beam with an energy of 1 GeV/u. (Note that for EURISOL the stable isotopes readily produced from natural or enriched feed material are all shown for a beam intensity of 1 μA.)

It can be seen that EURISOL generally yields the highest intensities out to the last known neutron-rich nuclei. This is only partially the case on the proton-rich side, where the more optimal choice for the production reaction possible with heavy ions combined with the half-life-dependent losses at EURISOL causes the yield curves far from stability to coincide or even cross below the GSI values. An exception is the element nickel that represents the group of particularly challenging elements for EURISOL since no proper target has at present been developed for its release.

For the production of the doubly-magic nuclei far from stability often serving as benchmarks, EURISOL is in a good position as seen from figure 5.2 [5,11]. While GSI will have the best intensities of ^{48}Ni the strongest ^{56}Ni beam is produced at EURISOL as shown in figure 5.1 by means of the off-line batch mode described in sect. 2.3.9 of reference [11]. Its fragmentation after post-acceleration would also lead to formation of useful ^{48}Ni intensities. For ^{78}Ni and many other exotic neutron-rich nuclei the high intensity of fission fragment beams at EURISOL will also open up the possibility of their production by secondary fragmentation. As an example the post-accelerated beams of ^{81}Ga and ^{132}Sn at EURISOL are optimum candidates for production of the exotic members along the *N*=50 and *N*=82 isotones, as seen from figures 5.1 and 5.3 [11,13].

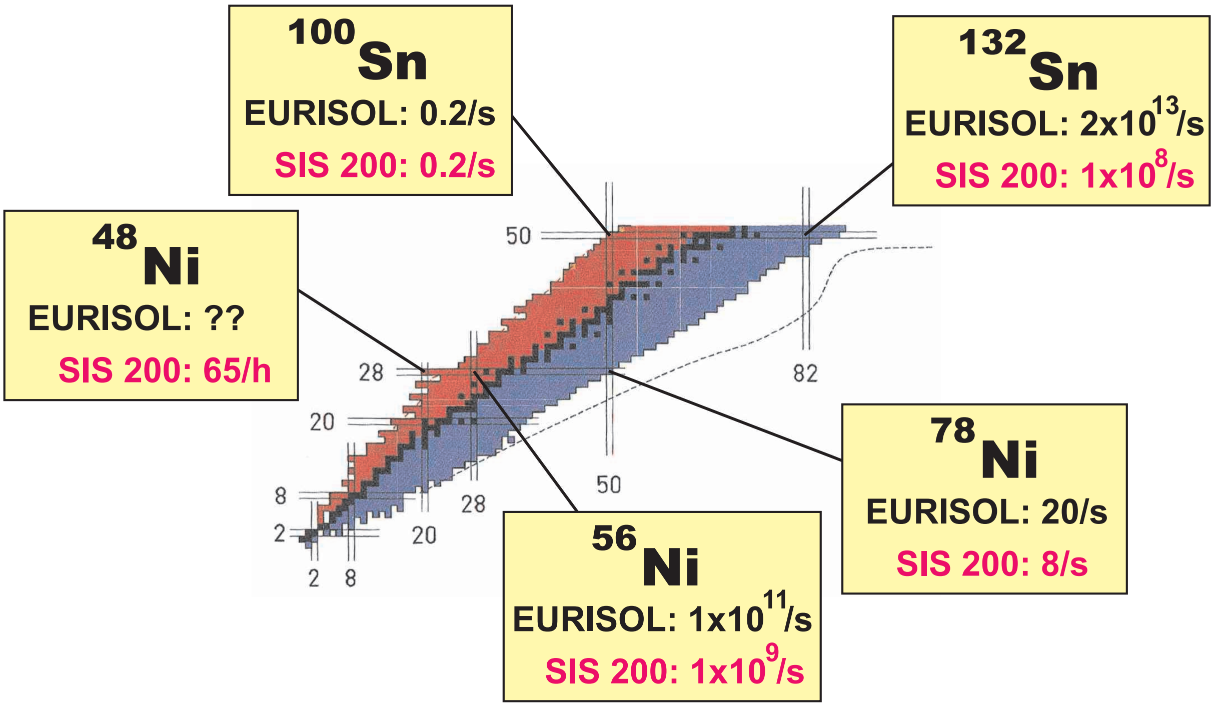


Fig. 5.2: The region of the chart of nuclides that illustrates the interesting doubly-magic nuclei far from stability and a comparison of their projected rates (as in figure 5.1) at EURISOL and the future GSI facility ('SIS 200').

While EURISOL give the highest intensity of the doubly-magic ^{132}Sn, ISOL targets for the production of neutron-deficient Sn isotopes that presently are under study (see section 2.7.2 of reference [11] and also reference [12]) also hold much promise for direct production of intense beams of ^{100}Sn at EURISOL. Alternatively, ^{100}Sn as well as many other exotic nuclei could be very favourably populated by fusion-evaporation reactions using the very intense post-accelerated neutron-deficient beams which would available at EURISOL, such as ^{50}Cr(^{56}Ni, α2n) or ^{40}Ca(^{62}Zn,2n), either for in-beam studies or for the production of low-energy mass-separated beams. This is illustrated in figure 5.1 where the yields of the most proton-rich Sn-nuclei measured as mass-separated ion-beams at GSI [12] in the reaction ^{50}Cr(^{58}Ni,αxn)$^{101\text{-}105}$Sn are compared to the more favourable reaction ^{50}Cr(^{56}Ni,αxn)$^{99\text{-}103}$Sn at EURISOL, assuming approximately identical cross sections for the two reactions.

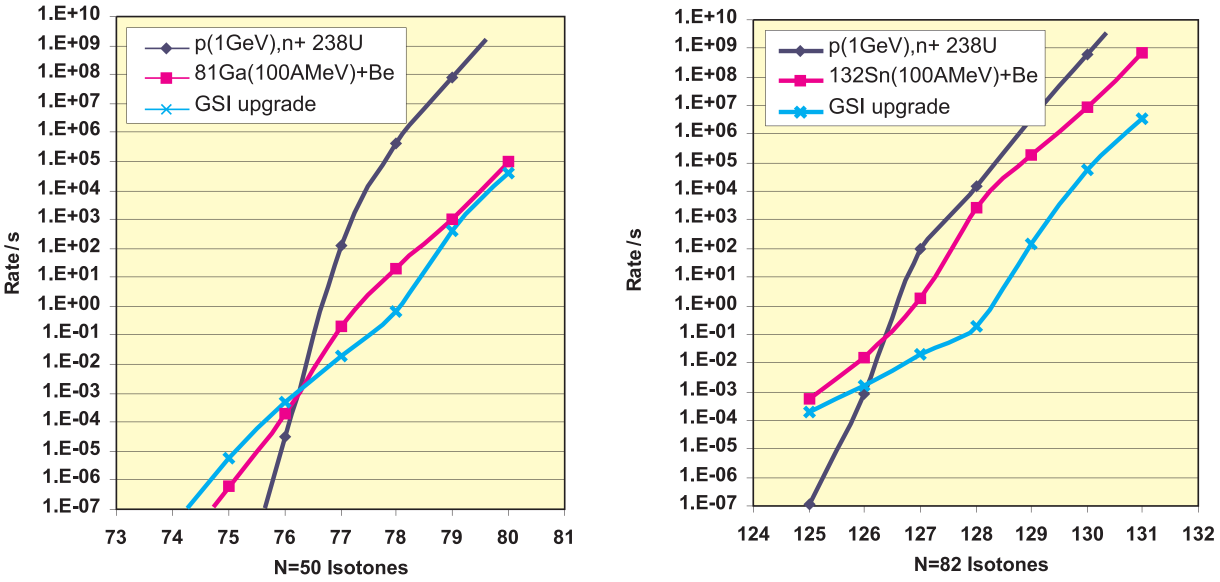


Fig. 5.3: Rates of the most interesting members of the N=50 and N=82 isotones produced at EURISOL in the 4-MW ^{238}U target and by fragmentation of the unstable projectiles of ^{81}Ga and ^{132}Sn compared to their production at the GSI upgrade by fragmentation of stable projectiles. The intensities of the ^{81}Ga and ^{132}Sn beams taken from table 2.1 of ref. [11] are 10^8/s and 10^{12}/s respectively. Note that the Ga beam intensities were extrapolated from a measurement at ISOLDE under very unfavourable conditions so that they should probably be up to an order of magnitude higher.

In conclusion, also in terms of intensity EURISOL compares very favourably to a heavy-ion fragmentation facility. By means of only a few examples, it has been is shown that the half-life-dependent decay losses of the most exotic species and the present lack of beams of all elements are strongly offset by the possibility to produce them in fusion and fragmentation reactions with the very intense secondary beams that would be available from EURISOL.

5.4 Fragmentation of RIBs

If very high intensities – up to several times 10^{12} particles per second – of neutron-rich RIBs are indeed produced at 100 *A* MeV with a 5-MW proton beam and two-stage targets, as suggested in table 2.2 of Section 5.1, then even more exotic neutron-rich nuclei could be produced by fragmenting these beams. Indeed, it has been shown [14] that the so-called 'cold-fragmentation' process could produce neutron-rich nuclei not very far from the fragmented nucleus with sizable cross sections: for example, the five-proton-removal channel from a 0.95 *A* GeV ^{197}Au (stable) beam still has a cross section of 10 nb, producing the neutron-rich nucleus $^{192}_{74}W_{118}$. If the cold-fragmentation process could be applied to neutron-rich RIBs, even more neutron-rich nuclei could be produced in this way.

In order to estimate the yields of such nuclei one could expect from this method, model calculations of a two-step reaction scheme for the production of neutron-rich secondary beams have been performed [15]. First, model descriptions of the cold-fragmentation process have been formulated using three different computer codes: (i) **EPAX** [16], a semi-empirical parametrisation of the fragmentation cross section; (ii) **ABRABLA** [17], a Monte Carlo simulation code describing the nuclear-collision process by the abrasion-ablation model for energies well above the Fermi energy; and (iii) **COFRA** [14], a cold-fragmentation code, which is a simplified analytical version of ABRABLA and which only considers neutron evaporation from the pre-fragments formed in the abrasion step.

The validity of these three codes has been tested by comparing their results with available experimental data, yielding the following conclusions [15]. EPAX is valid for stable projectiles because it is a fit to the existing data. ABRABLA and COFRA model the physical process and are thus expected to be better suited to exploring the unknown areas. COFRA can only be utilised when the proton-evaporation probability is much smaller than the neutron-evaporation probability, as is very likely the case for the fragmentation of neutron-rich nuclei; in this case, COFRA is much faster than ABRABLA and can thus be used to compute very small cross sections without too much computer time. However, the influence of the neutron excess of the projectile on the behaviour of the fragmentation cross sections is not explored sufficiently well by the available experimental data in order to allow for experimental verification of the differences found in the predictions of the different codes. Concerning the validity of the various codes at different energies for the fragmented nuclei (70 to 1000 *A* MeV), the consensus is that the model calculations can only be used with some precautions at energies below 200 *A* MeV.

With these reservations in mind, the three codes mentioned above were used [15] to estimate the fragment production rates from neutron-rich projectiles, either stable (^{136}Xe) or radioactive (^{132}Sn, ^{84}Se, ^{83}As, ^{82}Ge, ^{81}Ga, ^{80}Zn, ^{79}Cu), for different thicknesses of a Be target (20% and 50% of the range of the projectiles) and for different energies of the projectile (100, 200, and 400 *A* MeV). Intensities of the projectiles to be fragmented were assumed to be, in particles per sec (pps): 10^{11} for ^{132}Sn and from 10^{12} to 4×10^{6} for ^{84}Se to ^{79}Cu. These intensities are not unrealistic, as shown in table 5.2 (10^{12} for ^{132}Sn, 10^{9} for ^{81}Ga). The conclusions from these estimates are as follows.

The values of the EPAX calculations are about ten times higher then those obtained with ABRABLA, and are probably somewhat optimistic. The fragmentation of a ^{132}Sn beam of 10^{11} pps with an energy of 100 *A* MeV would yield the N=82 nucleus ^{124}Pd with intensities of between 2 and 4×10^{4} pps for Be targets of 20% and 50% of the range, respectively. By comparison, the production of similar rates of ^{124}Pd by fragmenting a stable ^{136}Xe beam would require a beam power of 15 MW, a completely unrealistic value. The production of the N=50 nucleus ^{78}Ni was also investigated by fragmenting various neutron-rich radioactive nuclei ^{84}Se to ^{79}Cu, at energies of 100, 200 and 400 A MeV, and with 20% and 50% targets. As an example, ^{78}Ni rates between 500 and 1300 pps would be obtained by fragmenting a 100 A MeV ^{81}Ga beam with an intensity of 10^{10} pps. By comparison, the production of 10^{3} pps of ^{78}Ni by fragmenting a stable ^{86}Kr beam would require 10^{18} pps of ^{86}Kr, an intensity which is completely out of reach.

The production of the neutron-rich nuclei ^{124}Pd and ^{78}Ni in the target, by the direct fission of ^{238}U by protons at 1 A GeV (either with a 1-GeV proton beam on a ^{238}U target or with a ^{238}U beam of 1 A GeV on an hydrogen target) is higher than the production rates mentioned above. However, these (and similar) neutron-rich nuclei are short-lived, and their extraction from an ISOL target would imply very large decay losses, as shown in Appendix C.

It is concluded by the authors of reference [15] that the two-step reaction scenario can be useful by profiting from the very high secondary-beam intensities to be obtained for specific neutron-rich nuclei by the ISOL method. For example, by extracting an abundant and long-lived nucleus like ^{132}Sn from an ISOL source and fragmenting it, one can reach those isotopes that have low ISOL efficiencies owing to their short half-lives or their chemical properties. In any case, the two-step reaction scheme gives best results when the mass loss in the fragmentation step is low.

At EURISOL, it is therefore proposed that the post-accelerator should be designed so as to be able to accelerate heavy ions such as ^{132}Sn to an energy of 100 A MeV, so that fragmentation method may be used to create (amongst others) extremely exotic neutron-rich isotopes.

5.5 Multiple-user aspects

EURISOL will provide beams to a large and diverse user community. In order to maximize the utilisation of these precious beams, a number of design options must make it possible to work in a multiple-user/beam-sharing mode. The basis of this approach would be addressed by provision of (at least) three production-target stations, which could in principle work in a simultaneous production mode by time-sharing of the driver beam.

The first RIB-sharing possibility would encountered at the low-energy mass separator. A careful design of the beam switch-yard at the focal plane of this separator should allow the simultaneous use of low-energy radioactive beams at collection stations for decay studies, solid-state studies, radioisotope production or other applications. Experience at ISOLDE suggests that both higher- and lower-mass isotopes can be selected from the exit of the pre-separator in addition to the main isotope chosen for post-acceleration. From this point onwards, therefore, a number of beams can be selected for further manipulation. Different energy domains would be served and for the option of a superconducting linac as post-accelerator, beam-sharing in the sense of one pilot user and a number of parasitic users, possibly even in another energy domain, should easily be realized.

We note here that for a linac solution, it could be possible to switch some of the post-accelerated beam to different areas, i.e. by using the output after the low-, medium- or high-energy stages of the linac, respectively, but this would of necessity be the same ion species. Where very exotic RIBs with only relatively low yields are concerned, this would be impracticable. However, provision could also be made for directing other ions from the pre-separator to a separate low-energy (1-MeV) accelerator, for astrophysical experiments, for example.

6 Key experiments illustrating the need for EURISOL

In order to illustrate the use to which experimental nuclear physicists – and others – would put the proposed EURISOL facility, a number of key experiments are discussed in this section. Additional information is presented concerning important astrophysical applications and the opportunities for medical use of radioisotopes which would be available from the facility.

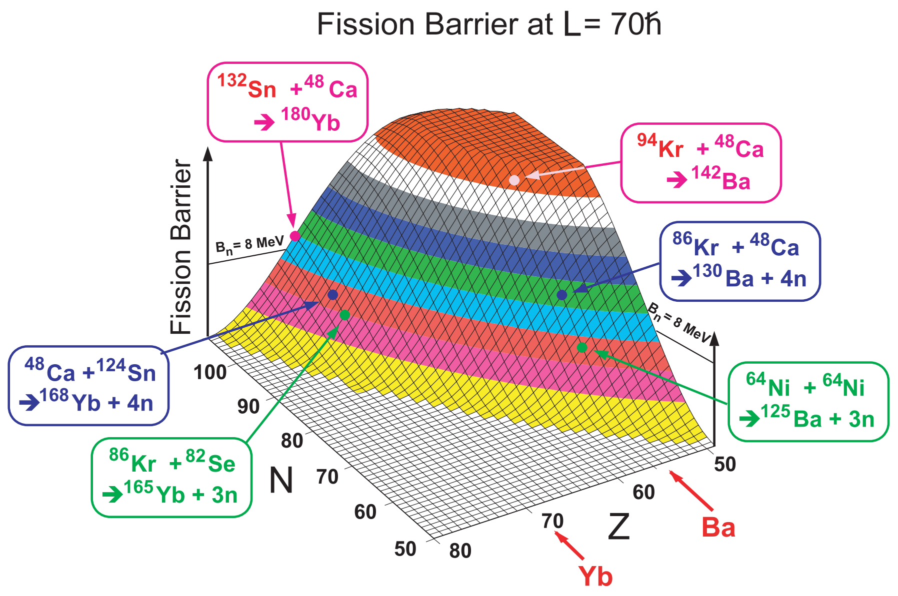
Each subject is discussed in detail in a box in the following pages, and below we simply list their titles.

- **Box 1: Neutron-rich nuclei as ultimate high-spin probes**
- **Box 2: The doubly-magic nucleus ^{78}Ni**
- **Box 3: Atomic non-conservation of parity**
- **Box 4: Phase-transitions of very exotic nuclei**
- **Box 5: Novae, X-ray bursts and the rp-process**
- **Box 6: Supernovae, neutron-star mergers and the r-process**
- **Box 7: Medical radioisotopes from EURISOL (1)**
- **Box 8: Medical radioisotopes from EURISOL (2)**
- **Box 9: The search for superheavy nuclei**

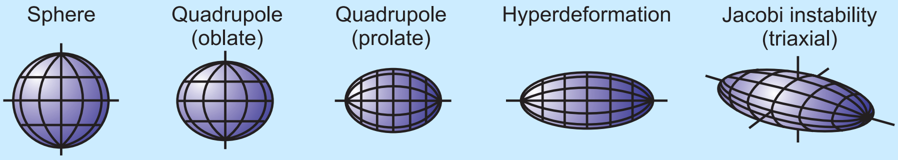
Neutron-rich nuclei as ultimate high-spin probes

Neutron-rich nuclei are the ultimate probe for high-spin studies since the neutron excess strongly reduces their “fissility”. Examples for new phenomena expected at the very highest spins are **hyperdeformed nuclei**, i.e. very elongated nuclear shapes with an axis ratio of 3:1, and the **Jacobi instability**, a shape transition – between oblate and prolate via a triaxial shape – predicted in the 19th century for a classically rotating object, which should be reflected in a sudden reduction of the rotational frequency of the nucleus (a “Giant Backbend”). Both effects should come into reach for experimenters when combining high intensity radioactive beams with the next generation gamma-ray spectrometers, such as the Advanced Gamma-Tracking Array, **AGATA**, a 4π-array of germanium detectors based on the novel technique of detecting and reconstructing all the gamma-ray interactions.

We still need to discover how extreme spin values (>80$\hbar$) are produced by the nucleonic movement, and we do not even know how much angular momentum a nucleus can sustain, nor how fast it can rotate.



Large neutron excesses (N>>Z) reduce nuclear fissility



Various types of deformation in nuclei.

Key experiments possible with EURISOL:

(a) A search for **hyperdeformation**:

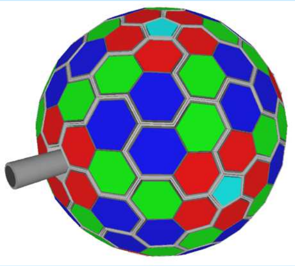
For the reaction ^{132}Sn (10^{10} pps) + ^{48}Ca → ^{180}Yb*, the cross section for forming a compound nucleus with angular momentum $L \geq 70$ is expected to be around 100 mb, leading to some 10^9 high-spin events per day.

(b) A search for **Jacobi instability**:

For ^{82}Ge (10^9 pps) + ^{48}Ca → ^{130}Te*, the expected cross section for forming nuclei with $L \geq 72$ is about 50 mb, leading to some 10^7 high-spin events per day.

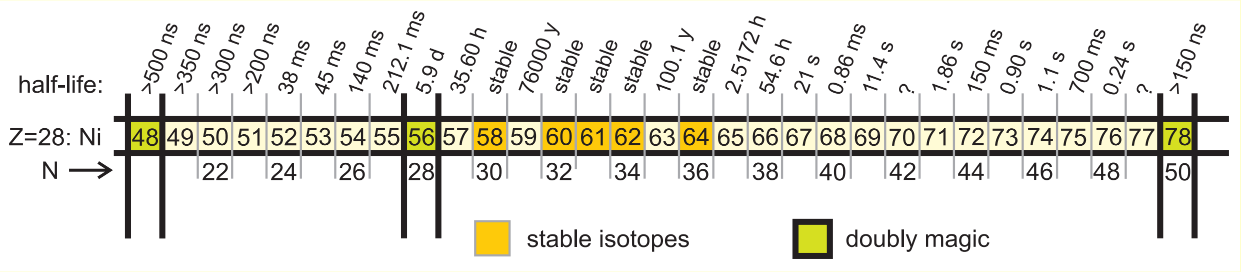
The **AGATA** array, with a total detection efficiency of ~50% and the ability to detect around 30 gamma rays per event, a probability of correctly identifying 6 of these of ~80%, should thus have a very high probability of observing such high-spin events.

The AGATA array



The doubly-magic nucleus ^{78}Ni

Both the number of protons (28) and the number of neutrons (50) of this nucleus are 'magic' for nuclei near the valley of stability. However, in this exotic nucleus the neutron-to-proton ratio is totally different to that seen close to stability. Does this dramatically alter the structure of ^{78}Ni?



Part of the chart of the nuclides, for Z=28.

So far, just three ^{78}Ni nuclei have been observed in an experiment at GSI, Darmstadt. The conclusion is that ^{78}Ni can be produced and can be studied if sufficient nuclei can be produced. With EURISOL it could be possible to make a detailed study of this key nucleus, which is important for our understanding of nuclear structure and also for nuclear astrophysics.

Coulomb excitation

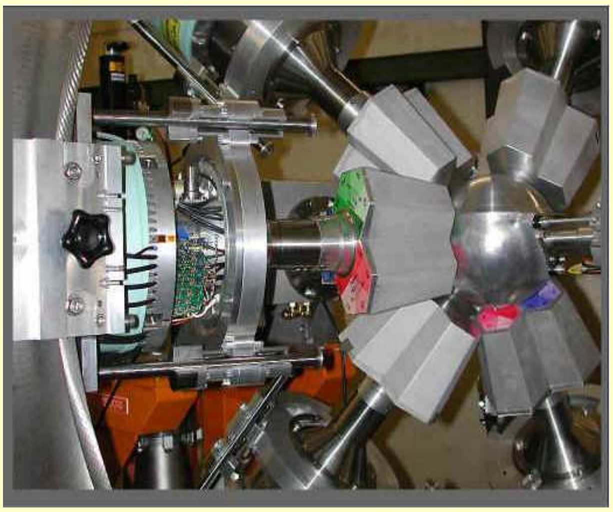
An old but powerful tool with which to learn about collective effects in nuclei – and to probe the 'magicity' – is Coulomb excitation of the nucleus of interest. Four decades ago this technique blossomed as intense beams of stable heavy ions could create the necessary flux of virtual photons to excite the nuclei of interest. The γ-rays emitted in subsequent de-excitation are observed and their energies and properties yield information on the structure of the nucleus.

With the advent of radioactive ion beams and powerful detection arrays, this excitation/de-excitation technique can now also be used for short-lived radioactive nuclei and pioneering experiments at first-generation ISOL-based radioactive ion beam facilities are taking place right now. They prove that Coulomb excitation at low bombarding energies is a clean and very sensitive probe of collective behaviour. A whole new horizon is opening up and one of the most intriguing cases is ^{78}Ni, one of the rare doubly-magic nuclei. Such a study should be possible at EURISOL, with a gamma-ray detector array like MINIBALL, EXOGAM or AGATA.

Beams of short-lived ^{78}Ni ions

The production of intense beams of short-lived nuclei at ISOL-based facilities is severely limited by the delay time of nuclei in present thick-target & ion-source configurations, and important decay losses occur. Estimates of the expected yield of ^{78}Ni are very difficult to make because of its poorly known half-life and the uncertainty in the gains which may be derived from target optimisation.

However, alternative target/ion-source systems could greatly reduce the delay time, and make such crucial experiments with rare nuclei like ^{78}Ni possible. Alternatively, recent calculations suggest that up to 1000 nuclei/second of ^{78}Ni may be obtained by fragmentation of exotic ^{81}Ga beams produced at EURISOL.

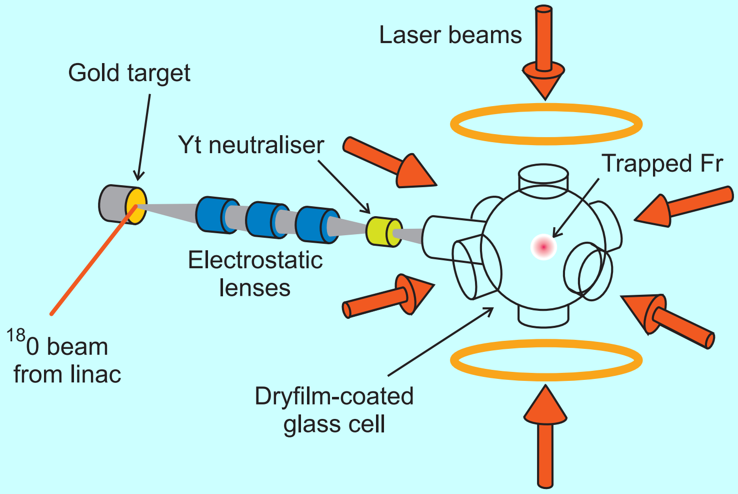


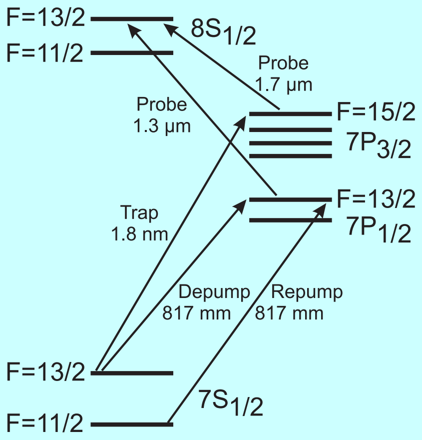
The MINIBALL detector array.

Atomic non-conservation of parity

Atomic Parity Non-Conservation (PNC) effects arise from the mixing of electronic states with opposite parity, owing to the weak interaction, which results in forbidden electric dipole transitions between states of the same parity. The PNC Hamiltonian depends on the coupling constants used in the Standard Model. High-precision measurements of these constants, together with improved atomic calculations, are expected to have significant implications for electroweak theory. Since PNC effects increase roughly according to Z^3, it is important to be able to test high-Z atoms, like francium. The motivation behind such measurements is to test the Standard Model at low momentum transfer, and to look for signatures of physics beyond the Standard Model

In experiments with Optical Traps, a wide rage of radioactive francium isotopes need to be delivered (as ions) at energies of a few keV and with intensities of at least 10^8–10^{10} ions per second. The ions are converted into neutral atoms and released inside a trap cell. Intersecting laser beams and appropriate magnetic fields provide velocity- and position-dependent forces that store and cool the Fr atoms in the centre of the cell. Atoms are then transferred into a second cell, where spectroscopic measurements can be performed. To observe a PNC signal, optical rotation or Stark interference techniques can be used. *(Figures below redrawn from originals from Stony Brook, NY:)*





Atomic and ion traps represent a novel technology to store and manipulate nuclei. Among the outstanding characteristics of these devices is the ability to confine nuclei within very small volumes and at very low temperatures. Studies performed with atomic traps, for example, led to the recent discovery of Bose-Einstein condensation. In recent years, traps have been developed to handle a number of radioactive ion species produced at complex accelerator facilities. With the ongoing improvements in the overall collection efficiency of traps and the intensities of ions which will become available at the next generation of RIB facilities, important new measurements for Nuclear Physics become feasible.

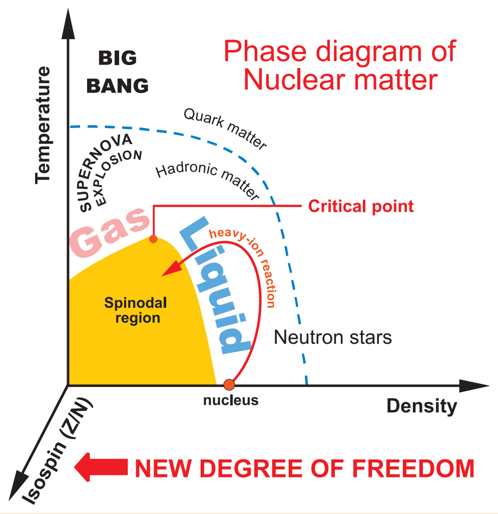
An example of this is the possibility of detecting, in coincidence, the lepton and nuclear recoils from the decaying nuclei without any distortion due to target thickness. The precision measurements of the correlation coefficients of the decay can give indications of the presence of new extra bosons. By making use of laser techniques, nuclei can also be polarized, and the measurements of asymmetry in alpha-decaying nuclei can reveal particular shape properties such as octupole deformations, etc.

In order to make such measurements, the present rates of production of Na, K, Rb, Cs and Fr (and also other non-alkali elements) need to be increased by several orders of magnitude. The EURISOL facility would provide such yields.

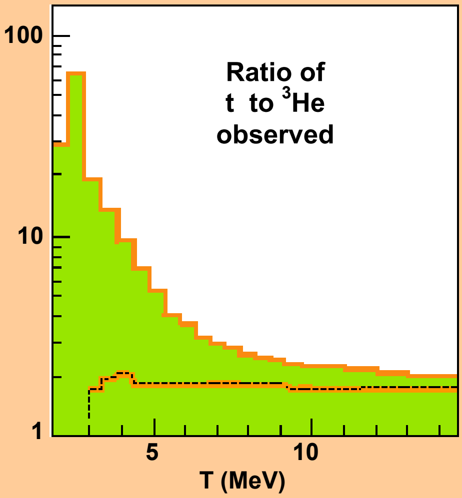
Other challenging new measurements which could then be addressed are electric dipole moments (for time-reversal studies), nuclear anapole moments (for observing PNC in the nucleus) and electron-neutrino correlations (for detecting the presence of new extra bosons).

Phase transitions of very exotic nuclei

The concept of an **"equation of state"** (EOS) for nuclei permits us to establish a link between nuclear physics and the general field of statistical physics of finite systems. In this context, a "liquid-gas" phase transition has been studied for energies below 100 MeV per nucleon, associated with the multifragmentation process. What still needs to be explored is the influence of the isospin (N/Z) degree of freedom on the EOS, and thus on the conditions for phase transition. Isospin fluctuations are explored together with density fluctuations. This leads to **"isospin distillation"** – a neutron-rich gas phase and a close-to-stability liquid phase (fragments). The instability region of the phase diagram is expected to shrink for extreme N/Z, which may inhibit phase transition. The conditions of observation of the phase transition will thus furnish information on the isospin-dependence of the EOS, at present very poorly known. EURISOL is expected to deliver beams with a large range of N/Z in the right energy range (20–100 MeV per nucleon), which will allow us to explore the isospin dependence.



Nuclear collisions take nuclei to temperatures and densities where they induce liquid-gas phase transitions.

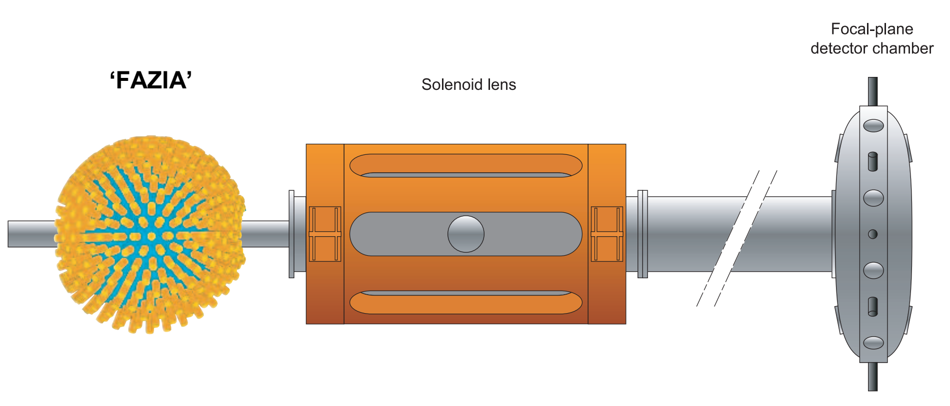


"Distillation" of neutrons in reactions involving neutron-rich systems.

In the liquid-gas transition of nuclei, a "distillation" may occur which may be seen in the ratio of tritium to ^{3}He observed: in neutron-rich systems a strongly neutron-enriched gas phase will be observed *(full curve at left)*, as compared with a more usual distribution *(dotted curve at left)*.

Key experiments

To explore the isospin-dependence for a wide range of N and Z, it will be necessary to investigate reactions using exotic beams, such as those with xenon beams ranging from ^{114}Xe + ^{40}Ca to ^{145}Xe + ^{48}Ca. The range of N/Z thus covered will be 1.08–1.61. The beam energies required are 20–100 MeV per nucleon, which corresponds well to the beams expected from the EURISOL facility. New detector arrays, like FAZIA, shown below, will be needed to take full advantage of the yield of particles from such experiments.



A new detector concept, based on advanced technologies, to identify fully the debris of the nuclear collisions studied.

Novae, X-ray bursts and the rp-process

Novae and X-ray bursts are the most commonly observed explosive astronomical events. They are presumably sites for explosive hydrogen burning and are responsible for forming the elements heavier than oxygen, involving nuclear reactions at high temperatures (above 10^8 K) and high densities. A close binary system, consisting of a main-sequence star and a white dwarf (for novae) or a neutron star (for X-ray bursts), undergoes an accretion process where ejected material is attracted by gravitational forces onto the surface of the white dwarf or the neutron star. The accreted material compresses the surface to ignite **nuclear reactions** under conditions of extreme pressure and temperature.

The hot CNO cycle

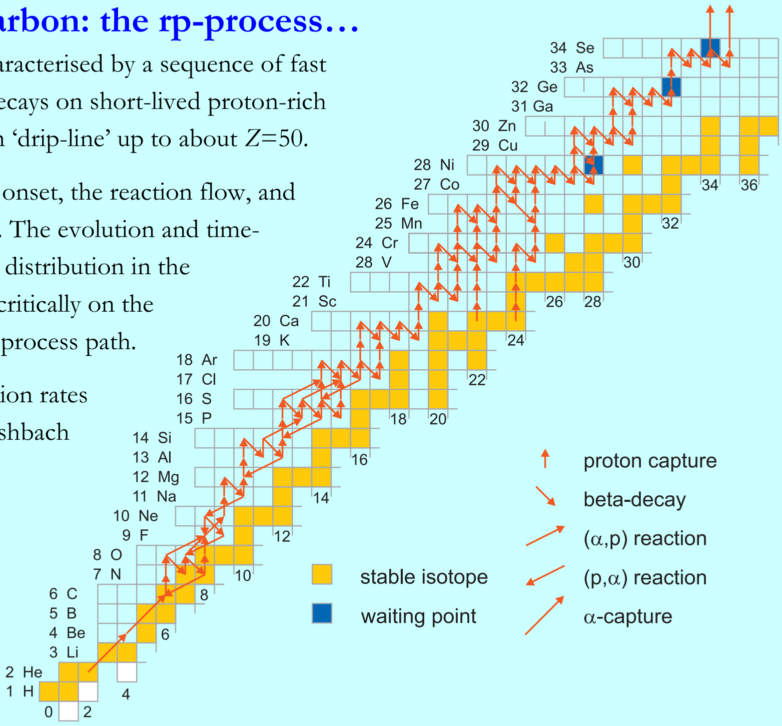
One source of this **thermonuclear runaway** is the hot CNO cycle. For example, gamma-ray emission from classical novae is dominated, during the first hours, by positron annihilation resulting from the beta-decay of ^{18}F, and is directly related to ^{18}F formation during the outburst. The $^{18}F(p,\gamma)^{19}Ne$ and the $^{18}F(p,\alpha)^{15}O$ rates remain uncertain and need further experimental and theoretical effort. Thermonuclear runaway will start only when the energy production becomes temperature sensitive, either via the triple-α process, which converts the initial ^{4}He into CNO material, or by breakout to the **rapid proton-capture** or **rp-process** which initiates the rapid conversion of these CNO isotopes into heavier nuclei. Two reactions currently candidates as triggers of the rp-process are $^{15}O(\alpha,\gamma)^{19}Ne$ and $^{18}Ne(\alpha,p)^{21}Na$.

Creation of elements above carbon: the rp-process…

The rapid proton-capture or rp-process is characterised by a sequence of fast proton capture reactions and subsequent β-decays on short-lived proton-rich nuclei, and is thought to run along the proton 'drip-line' up to about $Z=50$.

The corresponding reaction rates control the onset, the reaction flow, and subsequent luminosity of the explosive event. The evolution and time-scale as well as the final elemental abundance distribution in the ashes of the thermonuclear runaway depend critically on the nuclear decay and reaction rates along the rp-process path.

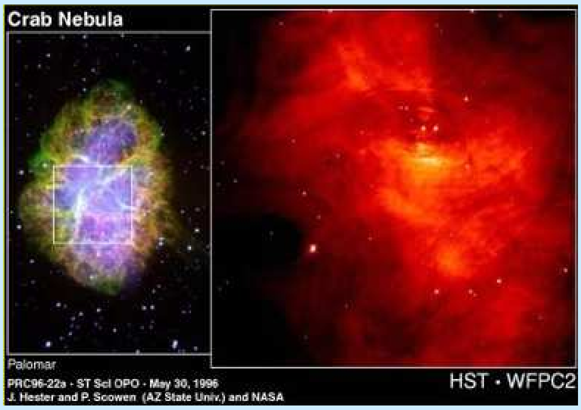
At present, most of the charged particle reaction rates for the reaction path are based on Hauser-Feshbach calculations. While these are supposed to be reliable within a factor of two for conditions of high density in the compound nucleus, discrepancies may occur for nuclei near closed shells or near the proton drip-line, where Q-values for proton capture are typically very small.



Nuclear reaction studies and nuclear structure studies on the neutron-deficient side of the valley of stability are essential for understanding these processes. Useful information should be obtained from measurements of alpha and proton capture on neutron-deficient radioactive nuclei below and near the double-closed-shell nucleus ^{56}Ni, like $^{45}V(p,\gamma)$, $^{46}V(p,\gamma)$, $^{47}V(p,\gamma)$ and $^{29}Mn(p,\gamma)$. Beyond ^{56}Ni, information in the Ge-to-Kr mass region is needed to determine the final fate of the neutron star crust. This concerns masses, beta-decay lifetimes, level positions and proton separation energies.

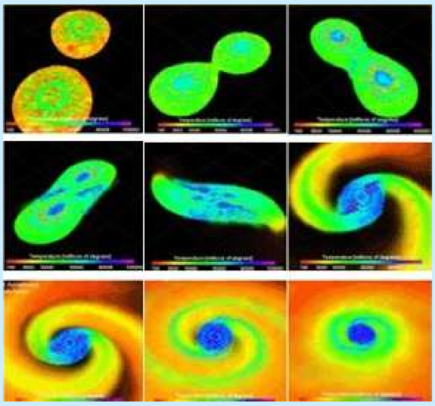
Supernovae, neutron-star mergers, and the r-process

Heavy-element nucleosynthesis is connected to two types of neutron-capture scenarios: the rapid or **r-process** and the slow or **s-process**. The latter occurs in red giant stars. For the r-process, two distinct stellar sites are frequently suggested: **core-collapse supernovae**, or **neutron-star mergers.** Understanding of the r-process will be based on close interaction between astronomy, cosmochemistry, nuclear physics and the modelling of explosive stellar scenarios.



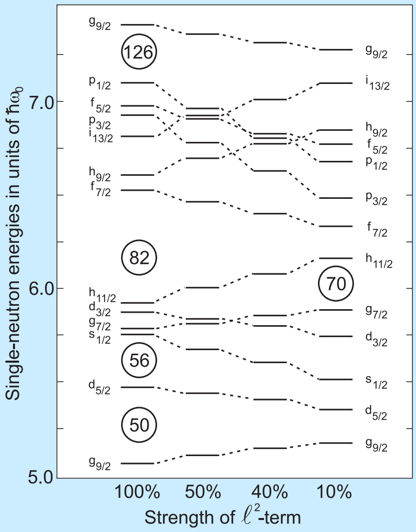
Left: The remnants of a supernova known as the Crab Nebula.

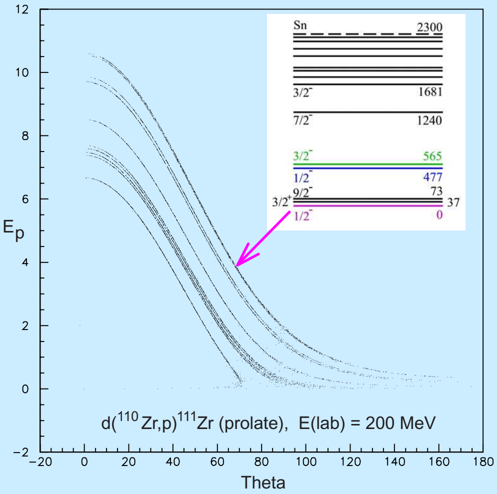
Right: Stages in the merging of two neutron stars, from a computer simulation.



The r-process

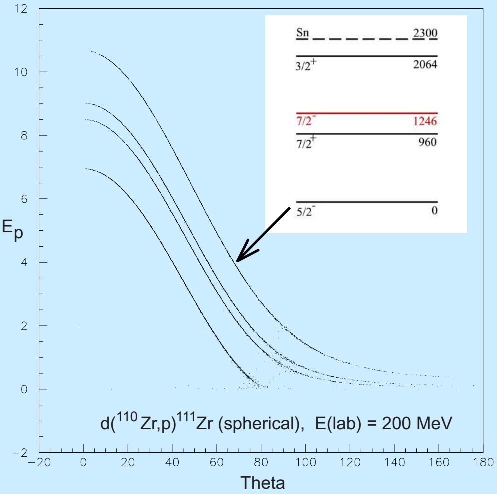
This process is characterised by a sequence of fast neutron-capture reactions and subsequent electroweak decays on short-lived neutron-rich nuclei. It is thought to run close to the neutron drip-line, up to at least thorium and uranium. The models need nuclear physics input for masses, electroweak decay properties and neutron capture cross sections. The r-process matter-flow and resulting abundances are greatly determined by the properties of neutron-magic "waiting-point" nuclei. However, recent nuclear spectroscopy indicates that the classical magic numbers may vanish near the neutron drip-line. The classical doubly-magic ^{122}Zr (Z=40, N=82) waiting point may be replaced by a new doubly-magic isotope ^{110}Zr (N=70). Shell-model calculations predict that ^{110}Zr is strongly deformed, but other models have recently suggested that – owing to shell-quenching – it is spherical.





Monte-Carlo simulations including target energy-loss and straggling for the d(^{110}Zr,p)^{111}Zr reaction.

Insets: predicted level diagrams. States in colour contribute to the resonant neutron capture probability.



The predictive power of the models can only be tested experimentally, by determining level schemes and n-capture cross sections. Angular distributions obtained from inverse-kinematics (d,p) reactions will show a distinct signature.

Medical radioisotopes from EURISOL (1)

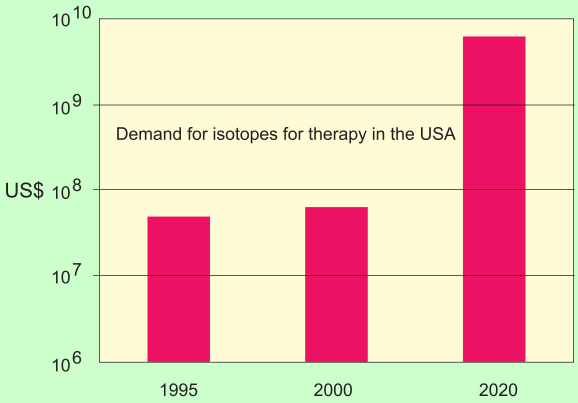
The systemic treatment of cancer using radionuclides is presently in a phase of transition from using less site-specific radiotracers to more selective bio-conjugates, such as radio-labelled monoclonal antibodies, peptides or olego-nucleotides. The limited number of receptor sites in the malignant tissue often requires **high-purity radionuclides** or even **new isotopes** with dedicated decay parameters. The present medical isotope production technology characterised by the success of ^{99}Mo/ ^{99m}Tc-generators is reaching its limitations concerning quantity, quality and flexibility. The new trend requires:

- improved quality parameters (specific activity and isotopic purity)
- meeting the rapidly growing demand (mainly for radiotherapy)
- new or exotic nuclides with dedicated α- or β-decay parameters.

The growing demand for medical radioisotopes is a worldwide phenomenon, though especially evident in the more developed countries.

The graph at right illustrates the predicted growth in demand for radioisotopes for therapy in the USA, and a similar near-exponential rise can be expected in Europe.

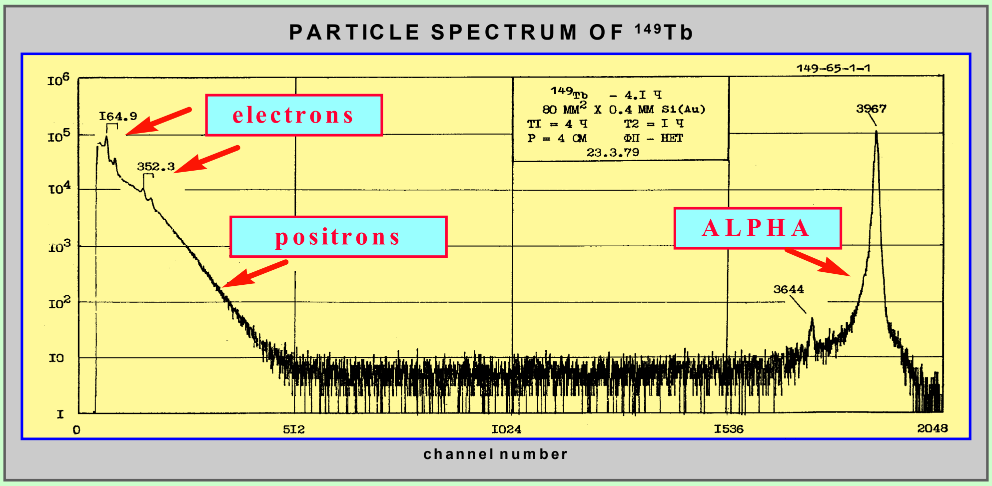
EURISOL will give free access to an unlimited variety of radionuclides without interfering with the physics experiments.



Combined with the ISOL physical and chemical separation technologies, this will permit enhanced R&D for bio-specific radiopharmaceuticals, the basis for new powerful methods in systemic cancer therapy. Many longer-lived radioisotopes will become available from used target material at EURISOL, and many of these will find new medical and therapeutic applications. Of the many possibilities, we illustrate here and overleaf some promising aspects of the radio-lanthanides for future cancer therapy.

Exotic isotope

The lanthanide isotope ^{149}Tb has great potential in future targeted alpha-therapy. The low alpha-particle energy (4 MeV) is most suitable for single-cell killing efficiency, as has already been demonstrated using samples of the radioisotope prepared at the ISOLDE facility at CERN.



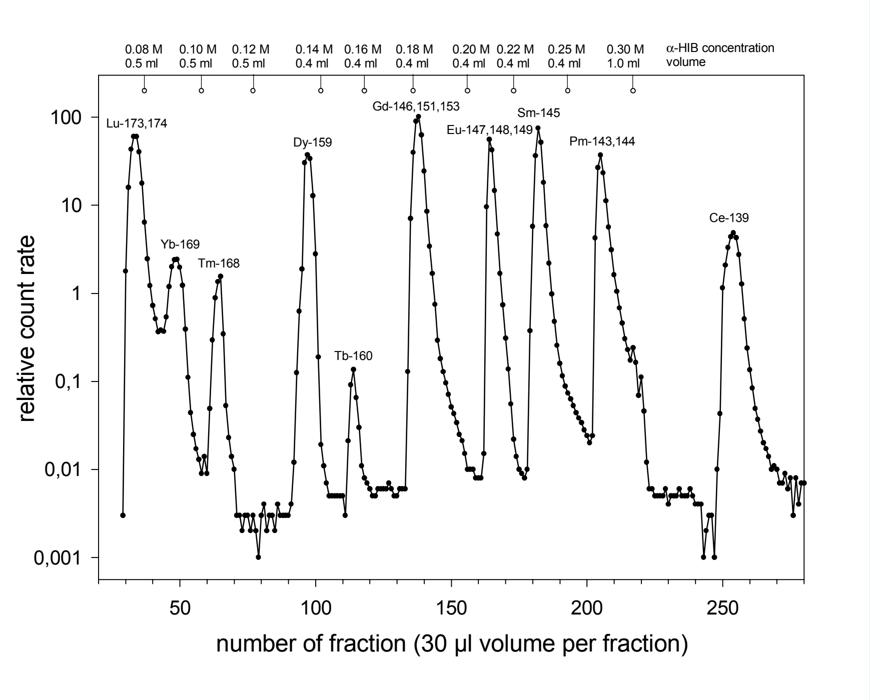
Particle spectrum of the lanthanide isotope ^{149}Tb

Medical radioisotopes from EURISOL (2)

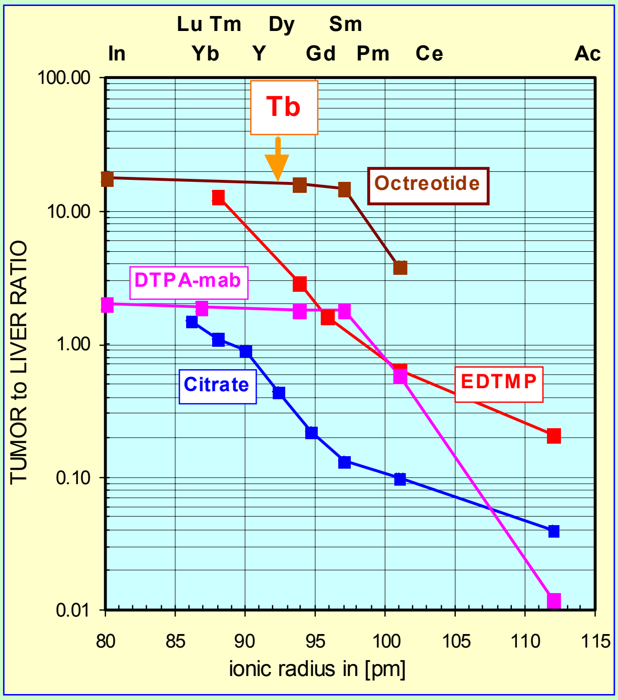
Universality

The simultaneous access to a large number of interesting radionuclides such as **radio-lanthanides** with extremely high quality parameters is a powerful impetus in support of systematic research activities in radiopharmaceutical development

The radio-lanthanides in the graph shown here were obtained by costly separation from Ta-targets from ISOLDE. However, at EURISOL these will be readily available from the converter target as residues in a configuration ideally suited for a very cost-efficient off-line mass separation.

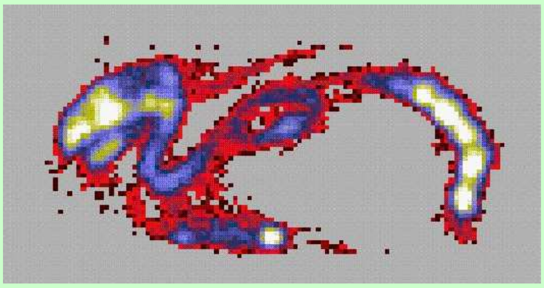


Metallic positron emitters for radio-immuno-therapy



Successful systemic radio-immuno-therapy needs an individual *in vivo* dosimetry of very high precision.

Metallic positron emitters, to replace the present beta-emitting therapeutic isotopes, together with PET (Positron Emission Tomography) will fulfil this task in future. The example of ^{142}Sm/Pm used here with a trial compound called EDTMP (shown below in a scan of a rabbit) illustrates the reality of this approach: this bone-seeking compound clears rapidly from the bloodstream, kidneys, etc.

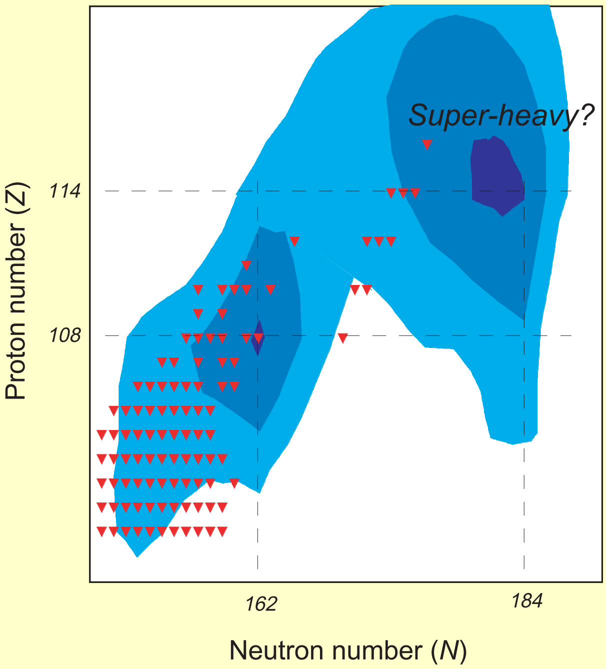


The search for superheavy nuclei

The synthesis of new heavy nuclei is of fundamental interest to physics and chemistry. The heaviest nuclei provide a laboratory to test our ideas on nuclear structure at the limits of large proton numbers. The production of new elements via nuclear reactions has been an active theme since the discovery of induced radioactivity and fission. Chemical properties have also been studied up to seaborgium (Z=106), but the methods used to show the existence of a new isotope or a new element are based on physical characteristics of each detected nucleus (velocity, kinetic energy) and, mostly, on its radioactive decay: a chain of a particles and spontaneous fission. Only a very few nuclei were ever detected for the heaviest elements. Chains of α-decays gave an unambiguous identification for Z up to 112. Recently, indications were obtained for the experimental evidence of elements 114 and 116.

Shell effects

The existence of elements above rutherfordium (Z=104) is the most spectacular consequence of the shell structure of nuclei. Indeed, if these nuclei were just "liquid drops" of charged nuclear matter, they would undergo fission immediately when one tries to form them. The additional shell effects modify the balance between repulsive Coulomb and attractive nuclear forces as a function of elongation, thereby creating a barrier against fission and allowing the nucleus to exist. It was first expected that nuclei would cease to exist at some value of Z, then re-appear again, to form an "island" around the next magic numbers of protons and neutrons. Actually the end of the nuclide chart will rather form a peninsula, since calculations predict – and experiments confirm – a continuous region of shell-stability extending from nuclei around hassium (Z=108), which have a deformed neutron shell at N=162, towards the next spherical doubly-magic nucleus. While there is agreement about the calculated location of the next neutron shell, N = 184, the next proton magic number was first thought to be 126, then 114, and now it may be 114, 120 or 126.



The nuclear chart in the vicinity of the possible "island" where long-lived superheavy nuclei may exist. Darker blue indicates greater predicted stability. Red triangles indicate known nuclei.

Fusion reactions

The production and identification of superheavies is very difficult. The compound nuclei formed by fusion must have an excitation energy small enough so that they de-excite by evaporating one or a few neutrons, thus leaving cold and detectable evaporation residues. If the excitation were larger than 15 to 30 MeV, these would de-excite via fission. At the corresponding incident energies, the fusion cross sections are extremely small and depend very sensitively on Coulomb repulsion in the entrance channel (high values should be avoided) and on the structure of the projectile and target nuclei (closed shells are favourable). The effect of these conflicting requirements is that from Z=112 onwards the cross section for fusion evaporation residues is in the picobarn range. With stable isotope beams it was established that larger residue cross sections are obtained when the compound nucleus has more neutrons. Since even the most neutron-rich stable projectile-target combinations lead to the neutron-poor side of the stability valley, this effect of neutron enrichment should be exploited with secondary neutron-rich unstable beams in order to come closer to the centre of the valley, thereby benefiting from larger cross sections. If EURISOL can deliver beams of doubly-magic ^{132}Sn with intensities of the order of 10^{11} particles/sec, the new "magic" **island of stability** with Z around 114 to 126 and N=184 may be reached, and long-lived superheavy elements may indeed be produced.

7 Proposed Research and Development and Synergies

7.1 List of RTDs relating to RIBs already accepted by the European Commission

In addition to the RTD proposal EURISOL, whose results are described in the present Report, the following RTD proposals related to radioactive ion beams have been accepted and supported by the European Commission under its Fifth Framework Programme (FP5):

- **'CHARGE BREEDING', Charge Breeding of Intense Radioactive Ion Beams.**
  (Contract HPRI-1999-50003.)

  Coordinators: Oliver Kester & Dieter Habs, Ludwig-Maximilians-Universität München, D-85748 Garching (Germany)

  Budget: 1.2 M€ **Period:** 01/01/2000 – 31/12/2003

  Objectives: development of the techniques for efficient charge-breeding devices.

  Relation to EURISOL: a high-performance charge-breeding device will critically influence the performances of the post-accelerator of any RIB facility, and in particular of EURISOL, since the final energies of the post-accelerator will depend on the charge state of the post-accelerated ions. This RTD is related to the work of the Target & Ion-Source Task Group, Appendix C, Section 5.

- **'EXOTAG', Studies of Exotic Nuclei using Tagging Spectrometers.**
  (Contract HPRI-1999-50017.)

  Coordinator: Rauno Julin, University of Jyväskylä, FIN – 40351 Jyväskylä (Finland).

  Budget: 1.5 M€ **Period:** 01/02/2000 – 31/01/2005

  Objectives: development of recoil implantation spectrometers that can be used in conjunction with recoil separators ('tagging spectrometers').

  Relation to EURISOL: to identify very rare events associated with RIBs, it is very often necessary to select the corresponding radioactive nuclei in a recoil separator and to identify them unambiguously in the focal plane of the latter, by detecting their emitted radiations with selective detectors. This RTD is related to the work of the Instrumentation Task Group, Appendix E, Section 3.3.1.

- **'R3B', Reactions with Relativistic Radioactive Beams.**
  (Contract HPRI-1999-50010.)

  Coordinator: Gottfried Muenzenberg, GSI, D-64291 Darmstadt (Germany).

  Budget: 0.8 M€ **Period:** 01/03/2000 – 28/02/2002

  Objectives: development of a next-generation experimental set-up for reaction studies with relativistic radioactive beams.

Relation to EURISOL: this RTD is closely related to RIB facilities using the In-Flight method. However, its results are relevant to the development of Fragment Separators, one of the proposed instruments for EURISOL. This RTD is related to the work of the Instrumentation Task Group, Appendix E, Section 6.2.

- **'INNOVATIVE ECRIS', New Technologies for Next-Generation ECRISs.** (Contract HPRI-1999-50014.)

  Coordinator: Alain Girard, CEA-Grenoble, F-38054 Grenoble (France).

  Budget: 1.9 M€ **Period:** 01/03/2000 – 28/02/2003

  Objectives: development of new technologies needed for a significant step towards higher currents and higher charge states in Electron Cyclotron Resonance Ion Sources (ECRIS).

  Relation to EURISOL: ECRIS ion sources are very likely to be used at EURISOL, and any improvement of their performance in the production of high charge states is relevant to EURISOL. This RTD is related to the work of the Target & Ion-Source Task Group, Appendix C, Section 5.

- **'TARGISOL', Optimal Release from ISOL Targets.** (Contract HPRI-2001-50033.)

  Coordinator: Ulli Köster, ISOLDE/CERN, CH-1211 Geneva 23 (Switzerland).

  Budget: 1 M€ **Period:** 01/11/2001 – 31/10/2004

  Objectives: optimisation of the release properties of ISOL targets.

  Relation to EURISOL: in any EURISOL target, it will be essential to increase the intensities of the ISOL/RIB by optimising the release of the produced radioactive species. This RTD is closely related to the work of the Target & Ion-Source Task Group, Appendix C, Section 2.5.

- **'ION CATCHER'**. (Contract HPRI-2001-50022.)

  Coordinators: Oliver Engels and Dieter Habs, Ludwig-Maximilians-Universität, D-85748 Garching (Germany).

  Budget: 1.4 M€ **Period:** 01/01/2002 – 31/10/2004

  Objectives: development of new techniques for effective slowing down, stopping in a gas cell and extraction of radioactive ions.

  Relation to EURISOL: a gas catcher for radioactive ions is one of the possible options for EURISOL. This RTD is related to the work of the Target and Ion Source Task Group, Appendix C, Section 6.

- **'HITRAP', An Ion Trap Facility for Experiments with Highly-Charged Ions.** (Contract HPRI-2001-50036.)

  Coordinator: H.-J. Kluge, GSI, D-64291 Darmstadt (Germany).

  Budget: 1.9 M€ **Period:** 01/11/2001 – 31/10/2005.

  Objectives: development of novel instrumentation for a broad spectrum of physics experiments with highly-charged heavy ions.

Relation to EURISOL: the trapping of radioactive ions is one of the techniques which will be used to study the ground-state properties of radioactive nuclei produced by EURISOL. This RTD is related to the work of the Instrumentation Task Group, Appendix E, Section 2.

- **'NIPNET', Novel Instrumentation for Precision Nuclear Experiments in Traps.** (Contract HPRI-2001-50034.)

  Coordinator: H.W. Wilschut, KVI, NL – 9747 AA Groningen (The Netherlands).

  Budget: 1.8 M€ **Period:** 01/11/2001 – 31/10/2004

  Objectives: creation of infrastructures for novel and precise experiments with exotic nuclides using ion and atom traps.

  Relation to EURISOL: as for 'HITRAP' above.

7.2 List of R&D items proposed for EURISOL

7.2.1 Driver Accelerator Task Group

The Driver Accelerator Task Group's report contains the following recommendations:

- Two items have high R&D priority: (a) construction of complete prototype accelerator sections for low-β elliptical SCRF cavities; (b) development of prototypical spoke, quarter-wave and re-entrant cavities with associated auxiliary RF components, to be tested with beam from existing facilities.
- Assuming that it is possible to establish common R&D programmes with other projects, it should be investigated whether common designs could be adopted. Important cost saving can be anticipated from this action.
- Such a common and 'synergistic' R&D programme should also provide the opportunity to investigate whether additional saving can be achieved by sharing the driver accelerator. From the technical point of view, pulsed driver accelerators provide a priori sufficient beam power for time-sharing the beam between two or even more users. However, at present it is still too early to draw conclusions about the opportunities for such an approach.

7.2.2 Target & Ion-Source Task Group

The Target & Ion-Source Task Group identified the following area where R&D would be necessary, in order to increase the intensity, variety and safe operation of EURISOL beams, and these areas are listed below in order of priority:

- The study and definition of the safety methods and laboratory standards that will be required for a high-intensity RIB facility (SAFERIB proposal).
- A substantial R&D effort with prototype construction and testing in order to define the engineering concept of the proposed compact molten-metal-cooled primary target needed to generate neutrons in the 4-MW target station for the production of fission fragments. It would be of similar size to the MEGAPIE project that plans to demonstrate safe operation of a liquid-metal spallation neutron target at a proton beam power of 1 MW.
- Design and testing of large, high-power fission and spallation targets that allow efficient release and cooling.

- An R&D program on laser excitation/ionisation for the production of pure beams of exotic nuclei in their ground state and/or an isomeric state, and determination of their moments using in-source spectroscopy.

7.2.3 Post-Accelerator and Mass Separator Task Group

The following topics are proposed by the Post-Accelerator and Mass Separator Task Group for further R&D:

- Study and construction of a test facility to establish the feasibility of the proposed TOF mass-separator.
- Developments and improvement of the RF-cooler technique.
- Continuation of developments on SC cavities, in order to reduce the cost of the superconducting linac and to increase its performances as much as possible.

7.2.4 Instrumentation Task Group

The Instrumentation Task Group identified a number of areas where R&D are required, and these are grouped below under the headings of the various Working Groups:

(a) Ion and atom traps: improvements and new applications

The studies of ground state properties and fundamental interactions at EURISOL require the development of a novel beam handling system, which provides cooling, bunching and purification of low-energy beams. In addition, **specific instrument R&D efforts** are needed in the various subjects that are currently being investigated within the NIPNET, HITRAP and ION CATCHER RTD projects, which run until 2004/2005.

(b) Polarised radioactive beams and special targets.

Polarised beams

R&D will be required to produce a variety of spin-oriented beams, such as:

- a 60 keV/*Q* primary EURISOL radioactive beam (ISOL-type) inducing the polarisation with circularly polarised laser light, either in a laser ion source or in a collinear set-up with the optical pumping method;
- a post-accelerated radioactive beam up to 2 MeV/u, using a stack of very thin foils, inducing spin-orientation via beam-foil and hyperfine interactions;
- secondary radioactive beams from a fusion-evaporation or projectile fragmentation reactions: both reactions are known to induce substantial spin-orientation in specific experimental conditions.

Special targets

This R&D program would be concerned with the development of gas, liquid, and solid light-particle targets for inverse kinematics reactions. We stress the importance of such developments for the efficient use of radioactive beams. Both polarised and non-polarised targets should be developed, and several different techniques should be investigated.

(c) Gamma-ray tracking

R&D is needed for developing ***gamma-ray tracking modules*** for the Advanced Gamma Tracking Array (AGATA). The AGATA project is based on the results obtained from the European TMR Network Project *Development of γ-ray Tracking Detectors for 4π γ-ray Arrays* in which a proof of concept for γ-ray tracking has been achieved.

(d) Signal analysis and application-specific electronics

Development of application-specific integrated circuits (ASICs) for nuclear physics

The realisation of multi-channel arrays with over 10 000 channels requires the development of high-performance, compact, integrated electronics. ASICs for nuclear physics are now in their infancy, but are starting to be developed for some applications (VAMOS, MUST II, etc.)

Charge and mass identification through pulse-shape analysis

Development of this technique is crucial for the construction of compact charged-particle and fragment arrays. It will alleviate our reliance on time-of-flight measurements which require long flight paths and thus large detectors. Research in this area includes development of electronics (signal digitisation), algorithms, and materials (nTD Si, CsI, etc.), and can thus be of interest to private companies as well as to institutional laboratories.

(e) Separators and spectrometers for EURISOL

This Working Group's activity has shown that in-flight separators and spectrometers are essential instruments for the anticipated European radioactive ion beam facility. Since they are quite expensive pieces of equipment, these instruments have to be chosen carefully in order to provide all of the necessary functions with a minimum number of devices. R&D is thus proposed to develop a spectrometer layout which should integrate the expertise developed in the major European laboratories around the most recent existing instruments to produce a high-performance new concept spectrometer, specially suited to the EURISOL requirements.

(f) Electronics and data acquisition systems for nuclear physics

This Working Group has proposed R&D to develop ***dedicated front-end electronics***:

- with **'on-detector':** compact, low-cost, reliable, low-power electronics, allowing easy portability for combining parts of different devices;
- with circuitry for preamplifiers, amplifiers, discriminators, digital coding, slow controls, calibration, testing, etc.; and
- digital signal sampling (DSS) and processing capabilities;

and also to develop ***data acquisition systems*** optimised for:

- the DSS technique,
- the **'free-running detector'** and **'trigger-less system'** concept.

Goals of the project:

- To develop low-cost (down to ~10 €/channel) ASICs for Si, planar-Ge and Ge to meet the dynamic range and resolution required, with suitably compact circuitry (~1 mm^2 per channel); to study the radiation hardening of the ASICs and all 'on-detector' circuitry.
- To develop low-power digital signal sampling and processing units with at least 12 bits at >2 GHz sampling frequency and 14 bits at a lower frequency; to built prototypes and evaluate a sampling procedure based on analogue pipelines and a 100-MHz ADC; afterwards to include signal digital analysis.
- To develop appropriate DAQ hardware and software for reconstruction, storage and on-line analysis of high-rate events, optimised for DSS technique and the 'triggerless' philosophy.

7.3 Synergies with other domains of research

7.3.1 General considerations

Throughout its investigations, the EURISOL feasibility study has carefully analysed its possible links and synergies with other projects and other research domains. Contacts have been established with experts from other scientific communities and their projects. We remark that the Town Meetings organised by the EURISOL Steering Committee have also been attended by scientists from other fields and, conversely, representatives from EURISOL have been invited to workshops outside their own community.

While analysing all aspects of an eventual construction project like EURISOL, one can typically identify and distinguish the following possibilities for synergy with other projected research facilities:

- interchange of information and experience,
- sharing of computer codes and capitalising on common design goals,
- collaborating on common R&D of dedicated components,
- adoption of major hardware developed by another project,
- design and manufacture of accelerator sections together with other project teams,
- construction of dual-purpose (or even multi-purpose) components of a common facility.

The appropriate level of collaboration is a delicate issue. Obviously the highly desirable aim of rationalisation of resources and avoidance of duplication of effort can only be reached in a meaningful way if such collaboration does not give rise to undue over-complication – thereby cancelling part of the anticipated gains – or relaxation of the respective technical specifications (i.e. compromising the scientific goals). A careful and balanced approach is therefore in order, the best way probably being a pragmatic one, so that by starting at rather ‘low’ level (e.g. collaborating on common R&D issues), one gradually implements higher levels of synergy as they appear applicable.

7.3.2 Research facilities offering possibilities for synergy with EURISOL

From the beginning of the EURISOL project, it was obvious that the driver accelerator was the principal component presenting potential links to other research facilities. Indeed, the design of high-intensity proton accelerators with energies in the GeV region is of great current interest for the following projects:

- ***Neutrino (and muon) factories.*** The CERN community is studying such a facility based on a pulsed linac of 4-MW average power, called SPL [18].
- ***Accelerator-driven hybrid reactor systems (ADS).*** This concept is proposed in Europe [19], in the USA [20] and in Japan [21] for nuclear waste incineration. The ‘European Roadmap’ [22] prepared by the Technical Working Group (TWG) quotes the 10-MW level for the demonstration facility, and the 50-MW level for the industrial extrapolation for the accelerator running in CW mode. A preliminary design study for a demonstration facility, funded by the European Commission is presently under way (PDS-XADS [23]).
- ***Spallation neutron sources*** for material science, presently under construction in the USA (SNS [24]) and in Japan (Joint Project [25]), or planned in Europe (ESS [26]). These projects use multi-MW linac accelerators in pulsed mode.

- ***Technological irradiation tools*** for the development of new radiation-resistant materials. These need neutron sources able to provide fluxes of some 10^{15} n/cm^2.s, corresponding to proton beam powers of the order of 10 MW.

Concerning the reference proton accelerator [27] of the PDS-XADS, it is obvious that the conceptual machine design is rather similar to that of the EURISOL baseline solution for a proton driver. In fact, we note that several institutions have been involved simultaneously in both projects, and certain work done for EURISOL has been applicable to the XADS and vice-versa. This will partly hold true for the future activities of both projects as proposed within FP6, i.e. the EURISOL Design Study and the Accelerator Working Package of the Integrated Project EUROTRANS on demonstration of transmutation. However, there will also be a very important and major difference which arise from the specific requirement for extremely high reliability of an ADS accelerator. It is as stringent as specifying only a few permissible beam 'trips' per year lasting longer than 1 second, because of the thermo-mechanical load to the sub-critical assembly, which is a dominant safety issue. Of course, such 'trips' would be rather irrelevant for a EURISOL facility where the reliability (and availability) requirements are those of a classical fundamental research facility. Even if many of the components are rather similar (e.g. the cryomodules) – and clearly some benefit is to be expected from this at least indirectly – the planned EUROTRANS R&D is exclusively focused on the reliability qualification rather than pushing the boundaries of performance (high energy, real-estate gradient, low cost, etc.) which are of concern for EURISOL.

An Integrated Project already approved and funded within FP6 is CARE, dealing with accelerator developments for high-energy physics. Relevant to the EURISOL driver is the IPPI task of CARE which concerns R&D for an intense pulsed proton injector, up to 200 MeV. While, in contrast to IPPI, the EURISOL baseline scenario relies on a CW accelerator, pulsed beams could also be acceptable and of interest for a multi-user facility, owing to the ease of time-sharing by switching pulses to different users. Furthermore, the CARE project will contribute to the development of local 'technological platforms' for developing superconducting technology and provides infrastructures which will be useful for the proposed EURISOL Design Study

7.3.3 Possible synergy between EURISOL and beta beams

This new topic has arisen during the last 2 years, based on an original idea published by P. Zuccelli [28]. Here an intense proton driver feeding a radioactive beam facility à la EURISOL, would produce a radioactive beam which would provide, in turn, by means of its β-decay, a single-flavoured neutrino beam of well-defined energy spectrum. In this so-called β-beam proposal, the post-acceleration of the radioactive beam to a very high relativistic γ-factor would provide simultaneously very good neutrino beam properties (because of the Lorentz boost), and would prolong the β-decay lifetime in the laboratory frame so that the decay ring can be suitably designed for short-lived emitters. ^{6}He and ^{18}Ne are envisaged as a prime candidates.

Originally the CERN SPS ($\gamma = 50$) was proposed as final post-accelerator, in connection with a neutrino detector placed in the underground Frejus tunnel laboratory (L = 130 km). The combinations of $\gamma = 500$, L = 730 km, and $\gamma = 2000$, L=3000 km, have also recently been discussed [29]. Here the final EURISOL post-accelerator could be the SPS with refurbished superconducting magnets, or the LHC. In view of these possibilities – which need much deeper investigations – and following recommendations by both High-Energy and Nuclear Physics committees (ECFA/ESGARD, NuPECC), it has been decided to include a β-beam study as part of the proposed EURISOL Design Study. This synergy at the highest level between two different scientific communities is a remarkable outcome.

8 Cost Estimates

8.1 Capital costs

8.1.1 Driver accelerator

Low-energy injector

The fabrication cost of such an injector for the EURISOL proton driver accelerator is estimated to be lower than the present construction cost of the IPHI project (see table 8.1 below). Thus the upper limit of the cost of the EURISOL injector should be about **10 M€**.

Table 8.1: IPHI components cost (M€).

SILHI source & LEBT	RFQ	Vacuum & diagnostics	RF & power supplies	Environment	Controls	TOTAL COST
0.6 M€	4.5 M€	1.1 M€	2.7 M€	0.8 M€	0.4 M€	**10.1 M€**

Intermediate-energy section

A first cost estimate has been done for the superconducting option, using 2-gap spoke cavities, with a total cost of **23.1 M€** (see table 8.2). Other options, e.g. using 4-gap half-wave resonators, or some re-entrant cavities instead of 4-gap cavities, all lead to very similar prices. All these versions can cope with acceleration of $A/q = 2$ ions.

Table 8.2: Estimated costs for the (2-gap spoke) 5–85 MeV linac.

Component	Unit price	Total
Niobium (per cavity)	15 k€	1.3 M€
Cavity fabrication with tuner & tank (each)	50 k€	4.4 M€
Coupler (each)	25 k€	2.2 M€
Quadrupole doublets (each)	40 k€	2.4 M€
RF (IOT) + power supplies (each)	80 k€	7.0 M€
Vacuum (per cavity)	5 k€	0.45 M€
Diagnostic (per cavity)	5 k€	0.45 M€
Cryostat (per metre of length)	20 k€	1.6 M€
Cryogenic system (300 W @2K)	-	2.3 M€
Controls	-	1.0 M€
TOTAL:	-	**23.1 M€**

Note that the cryogenic power needed for this superconducting solution is considered part of the capacity of the main refrigeration plant.

High-energy section (85 MeV– 1 GeV)

This preliminary cost estimate (see table 8.3) is based on more elaborated studies like SNS, ESS, ASH and SPL, and reaches a total amount of less than **90 M€**. It covers the investment on the main components of the high-energy section of the EURISOL driver up to 1 GeV. **The infrastructure, the buildings, the manpower and contingency factors are not included in this estimate.** Note that an upgrade to 2 GeV would need an investment of around 65 M€ (components cost only).

Table 8.3: Component cost estimate for the 85-MeV–1-GeV, 5-mA CW EURISOL linac.

Components	**Number**	**Unit Price (M€)**	**Total (M€)**	**Comments**
Cryomodules				
* Cavities	134	0.15	20.1	Cavities including couplers, tuners, etc.
* Cryostats	45	0.25	11.3	He tanks, thermal shields, instrumentation
RF System				
* RF Sources	134	0.07	9.4	Tubes & circulators
* Power Supplies	8 MW	0.7	5.6	
* Low Level	134	0.05	6.7	
* Wave guides	300 m	0.003	0.9	
Cryogenic system 2K				
* Refrigerator	4.5 kW	-	19.9	Cold boxes, compressors, storage
* Transfer lines	350 m	0.01	3.5	
Vacuum				
* Warm sections	45	0.03	1.4	Pumps, valves, beam tubes
Focusing				
* Quadrupoles	90	0.05	4.5	Including power supplies
Beam Diagnostics	-	-	1.5	
Controls	-	-	4.0	
TOTAL			**88.8 M€**	

8.1.2 Targets & ion sources

Target stations

Costs for the 100-kW target stations is based on existing facilities at CERN-ISOLDE and elsewhere (TRIUMF, SIRIUS proposal, etc.) The global sum for the Hg-jet target and its shielding and maintenance bay listed in table 8.4(a) is obtained from the SNS cost evaluation and discussions with its authors [30]. The cost of the 4-MW beam dump is taken from the CERN LHC [31] and the remaining items are roughly identical to those of the low-power stations. The cost of the necessary R&D program is estimated to be of the same order of magnitude as that of the current MEGAPIE program at PSI in Switzerland for developing a circulating Pb-Bi liquid-metal target insert for the SINQ spallation neutron source [32] at a beam power of 1 MW.

Cost estimate for the buncher and charge-breeder

The cost of the beam buncher and charge-breeder is based on the actual cost of the recently constructed REX-ISOLDE/REXTRAP/EBIS combination. In order to monitor and assure the correct emittance setting of the EURISOL ion sources, an emittance measuring system is included on both the off-line test separator and in the low-energy RIB beamlines.

Cost estimate for support laboratories and safety equipment

The cost of the needed infrastructure and associated support laboratories has been taken from ISOLDE, ISAC and LMU. While it includes cost for storage and disposal of the spent targets the **cost of decommissioning** of the entire target station has not been estimated.

The cost of equipment, buildings and construction staff needed for multiple target stations for a 100-kW proton beam and a single liquid-mercury-jet target for a 4-MW proton beam, with a charge-breeder and ancillary support equipment are tabulated below:

Table 8.4(a): Capital equipment cost estimate for multiple target stations and support laboratories.

Capital Item	Number	Estimated cost (k€)	Subtotals (k€)
Target stations up to 100kW			
Containment vessel		64	
Target shielding plugs	4	384	
Beam-stop assemblies	3	144	
Active water sump		128	
RHC scissor-lift table		320	
Transfer area, target plug transfer trolley		440	
Fitting out RHC cameras, jigs tooling etc.		96	
Posting transfer system		120	
Manipulators (6 arms): VNE90 including installation		1181	
Lead Glass Window (3 off), including frames		610	
RHC crane 30t with positional readout		72	
RHC crane rails (42m)		34	
Service area lighting and cameras		32	
Transfer flasks	1	128	
Ventilation systems with absolute filters, chilled water supply, ducts, controls and pressure gradients	1	1867	

Vacuum system with emission control for target, ion source and front-end extraction electrode assembly	3	300	
Cryopumping system in beamlines after the pre-separator for radioactive gas control	3	200	
Demonised water supply	3	32	
Cooling system, triple contained		288	
Front ends with extraction electrode assembly.	3	1400	
Pre-separator	1	213	
Target and ion source power supplies, high voltage faraday cage system with cabling	3	1200	
Laser laboratory & equipment for stepwise-resonant laser ion-source		1500	
Target inventory for 1 year of operation		3000	
Controlled access system		150	
SUBTOTAL			**13903**
High power target station up to 4 MW			
Mercury-jet spallation neutron source with pump and heat exchanger system and building	1	10000	
Development and tests of the target engineering concept	1	10000	
Shielding and hot cell for maintenance and repair	1	13000	
Large fission target and ion source	1	96	
He-cooled beam stop assembly of CERN, LHC/Neutrino-factory design	1	2000	
Cooling system for fission target and ion source, triple contained	1	288	
Front end with extraction electrode assembly.	1	467	
Target and ion source power supplies, high voltage faraday cage system with cabling	1	500	
Controlled access system	1	150	
Pre-separator	1	213	
Cryopumping system in beamlines after the pre-separator for radioactive gas control	1	67	
SUBTOTAL			**36781**
Trap/buncher/charge-breeder			
Trap/buncher	1	433	
Charge-breeder (EBIS)	1	680	
Trap-to-EBIS UHV beamline	1	147	
Emittance measuring and monitoring device	1	93	
SUBTOTAL			**1353**

Support laboratories			
Radiochemical laboratory for target development and uranium handling	1	2750	
Spent-target storage and disposal system	1	1733	
Radiation safety and emission control laboratory and emission control equipment	1	400	
Off-line separator and target test station	1	1070	
Test irradiation facility with pneumatic sample transport system.	1	20	
SUBTOTAL			**5973**
Total capital cost for target & ion source unit			**58010**

Table 8.4(b): Cost estimate for buildings for multiple target stations and support laboratories.

Building costs	**Estimated cost (k€)**	**Subtotals (k€)**
Target stations up to 100kW		
Excavation	223	
Bulk steel shielding	2234	
Target foundation & concrete cells	3851	
Building	13789	
Support laboratories		
Mechanical workshop for target and ion-source assembly (280 sq. m)	784	
Laboratory building and staff offices	5616	
Total cost of buildings for target & ion-source unit		**26497**

Table 8.4(c): Staff costs for construction of multiple target stations and support laboratories.

Construction staff	**Estimated cost (k€)**
Target station up to 100kW	
Management, scientific support and overheads	32
Staff costs total	2050
High power target station up to 4 MW:	
Management, scientific support and overheads	32
Staff costs, total	2050
Trap/buncher/charge-breeder	
Staff cost 2.5 FTE physicist/engineer 2.5 FTE technician	83
Total staff for TIS construction	**4247**

Summary of target & ion-source costs

Table 8.4(d) Summary of target & ion-source costs

Item	Cost (M€)
Total capital cost for target & ion source unit	58.0
Total cost of buildings for target & ion-source unit	26.5
Total staff for TIS construction	4.3
Target and Ion-Source total	**88.8**

8.1.3 Post-accelerator & mass separator

Here we consider the cost of a 100-MeV/u superconducting linear accelerator as the most promising option for the post-accelerator. For this exercise we assume that an accelerating field of 7 MV/m would be used, and we also assume that a charge-breeder will be able to provide ions of ^{132}Sn with a charge q=25+. (For a more modest q=6+, the cost would be 33% higher.)

Cost of a 100 MeV/u linac post-accelerator

This cost estimate is based on data acquired at LNL during the construction of the ALPI and PIAVE linacs, and includes all items that significantly contribute to the final cost. In the modular structure of a superconducting linac most of the manpower is included in the cost of the main blocks (e.g. SRL modules, cryogenics, buildings, etc.), which are delivered ready-made.

We have estimated that, for final assembly of a 100 (10) MeV/u linac starting from ready-made components, 60 (20) man-years are required. We have assumed a manpower cost of 0.1 M€/man-year.

In tables 8.5(a) and (b) below, the cost for shielding required in normal RIB operation is included in the cost of the buildings. Matching sections are also included. A rather large safety factor was included for the cryogenic power (50%) and a *20% contingency should be added to the final estimated cost.*

The linac building requires space to contain the beam-lines and cryostats, but also the RF equipment, magnet power supplies, vacuum controllers, cryogenic lines etc. An area of about 10 m^2 per metre of linac is more than adequate for this purpose. Additional space for the main components of the cryogenic plant (liquefiers, compressors, etc.) is not required if the helium is provided by the main cryogenic system of the EURISOL driver linac.

Table 8.5(a): Linac construction cost estimate for the nominal case: 7 MV/m, q=25+.

Item	Cost (M€)
Cost of the linac	46.5
Cost of the RFQ	3.0
Cost of the cryogenic plant	4.3
Cost of matching sections	2.5
Cost of controls (~5%)	2.7
Total cost of post-accelerator (M€):	**59.0**

Summary of post-accelerator costs

Table 8.5(b): Total estimated costs for the post-accelerator.

Item	Cost (M€)
Total cost of post-accelerator	59.0
Estimated cost of construction manpower (60 FTE-years @ 100 k€ each)	6.0
Estimated cost of buildings	1.6
Total cost for post-accelerator, including construction & buildings (M€):	**66.6**

Mass-separator costs

Two different types of mass-separators were suggested: a 'time-of-flight' separator and a more conventional 4-dipole separator using beam cooling to reduce the emittance and thereby achieve the required high transmission and high resolution.

The preliminary cost estimate (in table 8.6) includes a 20-m long beam line, the dedicated bunching system, magnets, fast chopper, and the dedicated control system. **The estimate does not include the associated beam lines.**

If the more conventional type of separator were used, employing 4 dipole magnets and an RFQ cooler, we anticipate that the cost would be very similar to this estimate.

Table 8.6: Cost estimate for the components of the time-of-flight separator.

Components	Cost (M€)
Linear buncher ($f= f_{RF} \approx 8$ MHz)	0.09
Chopper 1 (f_{RF} =8 MHz, V_{MAX}= 600V)	0.05
Bending Magnets (6 dipoles)	0.25
Focusing elements (7 quadrupoles + 1 solenoid)	0.06
Chopper 2 (non-resonant, f_{RF} =8 MHz, V_{MAX}=5 kV)	0.05
Buncher for matching to post-accelerator	0.09
Associated detectors (micro-channel plates)	0.05
Control system (~5% of total cost)	0.06
Other equipment (vacuum, beam-line, NMR, etc.)	0.30
Total	**1.00**
Installation (manpower)	0.20
Total cost including installation (M€):	**1.20**

8.1.4 Cost of instrumentation for EURISOL

Table 8.7: Instrumentation costs.

Area of Research	Cost (M€)	Cost (M€)
Techniques for ground state properties		**10.45**
• Mass measurements (Penning trap, TOF, magnetic)	3.70	
• Optical spectroscopy (CW, low and high-rate lasers)	2.50	
• High-energy experiments (HFI magnets)	0.90	
• Fundamental interactions (Penning & Paul traps, MOT)	1.45	
Solid state physics		**0.50**
Biophysics		**0.20**
Nuclear spectroscopy		**3.50**
• In beam spectroscopy (CP, e, n, fast timing, etc.)	1.05	
• Decay spectroscopy (focal plane detectors)	2.45	
Gamma-ray tracking		**20.00**
• Modular γ-ray array (50 % of AGATA)	20.00	
Reaction studies with RIBs		**20.00**
• GRAPA, Array for light charged particles & gamma rays	4.200	
• FAZIA, Four-π A and Z Identification Array	10.00	
• Neutron Arrays	2.80	
• Other ancillary detectors	0.50	
• Special targets (gas, polarised, radioactive)	2.50	
In-flight separators and spectrometers		**14.00**
• Spectrometer for astrophysics studies	3.00	
• Gas-filled recoil separator	1.00	
• Electromagnetic separator	2.00	
• Magnetic ray-tracing spectrometer	3.00	
• Fragment separator	5.00	
New techniques and probes		**4.00**
• Muon and antiproton trap facility	4.00	
Data acquisition system (rough estimate)		**5.00**
Beam lines		**7.50**
• 150 m @ 50 k€/m	7.50	
TOTAL cost of Instrumentation (M€):		**85.15**

Note that installation costs for these instruments is not included in the above estimate. User laboratories might possibly contribute manpower to help with installation of these devices.

8.1.5 Summary of costs supplied by Task Groups

Capital cost details by Task

Table 8.8: Summary of capital costs.

Item	Cost (M€)	Cost (M€)
Driver accelerator:		
Injector (IPHI component cost)	**10.1**	
Intermediate-energy: component for a (2-gap spoke) 5–85 MeV linac	**23.1**	
High-energy: components for an 85-MeV to 1-GeV, 5-mA CW linac	**88.8**	
TOTAL: Driver accelerator		**122.0**
Target stations, ion sources & support laboratory equipment:		
Target station for 3 targets for proton beams of up to 100 kW	**13.9**	
High power **target station** for 1 target with a 1-GeV proton beam of up to 4 MW	**36.8**	
Trap/buncher/charge-breeder	**1.4**	
Support laboratories	**6.0**	
TOTAL: Target stations		**58.1**
Post-accelerator & mass-separator:		
Post-accelerator costs for 100 MeV/u linac, 7 MV/m, charge state q=25+	**59.0**	
High-resolution, low-energy mass-separator	**1.4**	
TOTAL: Post-accelerator & mass-separator		**60.4**
Instrumentation:		
Techniques for ground state properties	**10.5**	
Solid state physics	**0.5**	
Biophysics	**0.2**	
Nuclear spectroscopy	**3.5**	
Gamma-ray tracking	**20.0**	
Reaction studies with RIBs	**20.0**	
In-flight separators and spectrometers	**14.0**	
New techniques and probes	**4.0**	
Data acquisition system	**5.0**	
Beam lines	**7.5**	
TOTAL: Instrumentation		**85.2**
TOTAL (capital costs, excluding buildings & manpower, no contingency):		**356.4**

Buildings

Costs for buildings (and concrete shielding) were explicitly estimated only for the **target/ion-source areas and support labs (25.7 M€)**, and for the **post-accelerator linac building (1.6 M€)**. Building costs for the areas not included above can be estimated by comparison with other projects.

For the **driver accelerator** we can refer to the **SNS report** for a 1.33 GeV linac: the estimate (in 1966 prices) for the linac tunnel (650 m × 5 m) plus the same length of service buildings (650 m × 15 m) was **24.5 M€.**

Costs for all the **experimental areas** can be calculated at approximately 10 k€/m^2, including standard concrete shielding walls or shielding blocks, cranes, cabling and services, etc. Thus for a layout of some 16 000 m^2 (e.g. 150 m × 100 m or equivalent), the cost will be approximately **150 M€.**

Other buildings

We have included **office space** for management, administration and research scientists (other than for the Target/Ion-Source laboratory staff). (Existing site infrastructure, where it already exists, may provide for this.) Typically, an area of standard office building of some 8000 m^2 of floor space would be required for administration, maintenance and research. At a cost of ~1.5 k€/m^2 this would give a total cost of approximately 8000 × 1.5 = **12 M€**.

Additional **workshop** space, **stores** and **power-supply rooms** should also be provided – about 150 m × 20m = 3000 m^2, to standard industrial building design @ 1 k€/m^2), costing **3 M€**.

Also needed are **control rooms, service labs, etc.** for the accelerators (200m × 50m = 1000 m^2, costing **1.5 M€**)

User electronics and data-acquisition areas could perhaps be inside the experimental halls, and could then be of light-weight (indoor) construction. However, this is expensive space, and external user areas would probably be cheaper. (1000 m × 20m = 2000 m^2, costing **3 M€**)

A **restaurant** (~500 m^2), **auditorium** (200 m^2) and some on-site **accommodation for users** (e.g. ~500 m^2) would also be needed (**2 M€**). (Existing site infrastructure, where it already exists, may provide for this.)

Approximate costs for all areas are indicated in the table below:

Table 8.9: Summary of estimated total building costs for EURISOL.

Buildings	**Area (m^2)**	**Cost (k€/m^2)**	**Cost (M€)**
Driver linac + service buildings *(from1996 ESS 1.33 GeV costs)*	N/A	N/A	24.5
Target & ion-source buildings, shielding *(from TIS report)*	N/A	N/A	26.5
Post-accelerator buildings *(from Task Group report)*	N/A	N/A	1.6
Accelerator halls & experimental areas (rough estimate)	15 000	10	150
Offices/labs/administration	8000	1.5	12
Control rooms, computers and service labs	1000	1.5	1.5
Workshops, stores, power supplies, cryogenics	3000	1	3
User electronics & data acquisition areas	2000	1.5	3
Restaurant, auditorium, visitor accommodation	1200	1.5	2
TOTAL BUILDING COST (M€):			**224.1**

The very detailed estimates for 'civil construction' in the **RIA project** in the USA from ANL and MSU agreed within ~5%, but the costs vary between \$200 and \$600 per square foot, depending on the type of building. This indicates the difficulty of making such an estimate for EURISOL without a detailed study of building layout. The RIA estimate for 'civils and utilities' totalled **\$126.5M** in 2000, a figure which is possibly on the low side.

However, in the **ESS costs** [33] we find **157 M€** (in 1996 values) for buildings for a linac plus a small ring and target areas, etc. plus **87 M€** for utilities (electricity, water, ventilation), i.e. **244 M€**.

The total construction cost for **the SNS** presented in the FY 2003 Congressional Budget Request [34] is estimated at $182M plus an additional $21M for utilities, i.e. a total of **$203M**.

Similarly, the **GSI costs** [5] for proposed buildings, tunnels, cranes, services, etc. total **225.5 M€.** This suggests that the estimated cost of buildings for EURISOL is at least in the right ballpark, though it may be on the high side.

Note that the **buildings contribute about 1/3 of the total project cost**. Of some concern is that the 10 k€/m^2 (including shielding, overhead cranes and a wide range of additional utilities) is a rather arbitrary figure, and is in general expensive compared to basic building costs. For this reason, no contingency factor is added to the building costs in the summary given below.

8.1.6 Summary of Total Capital Costs

Table 8.10: Total capital costs for EURISOL

Capital items	**Cost (M€)**
Driver accelerator	120.0
Target stations and ion sources + labs	58.8
Post-accelerator & mass-separator	60.4
Instrumentation	85.2
SUB-TOTAL:	**324.4**
+ 20% contingency factor	64.9
SUB-TOTAL:	**389.3**
Buildings	224.1
GRAND TOTAL:	**613 M€**

8.1.7 Installation Manpower

Note that manpower for installation is NOT included in the estimates given above for installation of the technical items shown in the table below. The cost of installation and commissioning of devices listed under instrumentation has not been estimated, but could be met by contributions of manpower from external user laboratories.

Table 8.11: Installation costs for EURISOL.

Devices	**Cost (M€)**
Driver accelerator (estimated from post-accelerator)	6.0
Targets & ion sources	4.2
Post-accelerator	6.0
Mass separator	0.2
Instrumentation	(not estimated)
TOTAL installation cost (M€):	**16.4**

Items not included in the costing:

(a) Project Management;

(c) R&D costs and Conceptual Design effort;

(d) Installation of experimental apparatus (see note above);

(e) Environmental Impact Analysis, permits;

(f) Costs of commissioning of elements sub-systems and systems.

These costs, which can be considerable, depend very much on the funding of the Design Study and later Engineering Study phases of the EURISOL project, and the amount of R&D which is done during this time. Since some items are described as using 'existing technology', the amount of R&D required for these would be small. For the rest, the reader is referred to section 7 of this report.

8.1.8 Conclusion

The capital cost of buildings, accelerators and all ancillary equipment needed for the proposed EURISOL facility is estimated to be some **613 M€**, within an error of some 20%.

To this would have to be added any R&D costs not covered by prior funding, plus installation costs (**~16–20 M€**) if existing manpower at the chosen site or manpower from user laboratories could not provide for this.

8.2 Operating costs

8.2.1 Driver accelerator operation

A preliminary operating cost estimate is given for the entire driver linac in table 8.12. This costing is based on an operational time of 80% and on an electricity cost of 0.055 €/kW.h. **Staffing and maintenance costs are not included in this estimate**.

Table 8.12: Electricity cost estimate for the whole 1-GeV, 5-mA CW driver linac.

Section	AC power for RF (MW)	AC power for cryogenics (MW)	Electricity cost (M€/year)
Low-energy	2.1	-	0.8
Intermediate-energy	1.0	0.3	0.5
High-energy	8.5	3.2	4.5
TOTAL:	**11.6**	**3.5**	**5.8 M€/year**

8.2.2 Post-accelerator operation

The costing shown in table 8.13 for a superconducting linac post-accelerator is based on an operational time of 80% and on an electricity cost of 0.055 €/kW.h, as for the driver accelerator:

Table 8.13: Electricity costs for a superconducting linac post-accelerator.

Section	AC power for RF (MW)	AC power for cryogenics (MW)	Electricity cost (M€/year)
RFQ	(negligible)	(negligible)	-
Linac	2.4 (10W x 240 cavities)	4.25	2.56*
TOTALS:	**2.4**	**4.25**	**2.56**

* Electricity cost = 6650 kW x 0.8 x 365 x 24 x 0.055 €/kWh = 2.56 M€/year

8.2.3 Target and ion-source operation

The operating cost of approximately 4 M€ given in table 8.14 is obtained by extrapolation of the combined actual target and manpower cost at ISOLDE and the target laboratory operation at LMU in Munich, assuming a yearly operation of 7000 h for physics and machine development. The yearly exploitation cost is close to 5% of the capital investment cost of 100 M€ when it is scaled to the relevant running period. This 5% rule also fits well with the exploitation budget within the CERN accelerator sector for similar high-tech facilities such as Linac 3 and ISOLDE. The precision of this estimate depends strongly on the construction and lifetime of the large fission target and the Hg-jet neutron source. Adding to the uncertainty are the still-to-be-evaluated safety requirements and the actual cost of disposal of the spent targets.

Table 8.14: Operating costs for the target stations (see text).

Operating costs for 1200 8-h shifts	Cost (k€)
Target and ion-sources	3000
Staff for operating and maintenance: 15 full-time equivalents	700
Service and maintenance of support laboratories	100
Helium and nitrogen cost	2
Disposal of radioactive targets	120
TOTAL OPERATING COST for targets and ion sources:	**3.92 M€**

8.2.4 Staffing and maintenance

We do not have manpower or operational costs for beamlines or instrumentation, and we only have figures for electricity costs for the driver and post-accelerator. The manpower available at any specific site will also greatly influence the estimated additional manpower needed for operation.

The ESS report [33], for example, gives a table of operating costs as global staff and electricity costs, respectively, plus an operating cost for each area of the facility. (A major contribution to the ESS estimate is for **'scientific utilisation',** including staff for each 'instrument'.)

Operational costs for the RIA project were estimated at **$65M** by both ANL and MSU. This includes operating staff (90 full-time equivalents, including 20 postdoctoral researcher staff).

The post-doctoral research staff at an existing accelerator facility would probably not be increased greatly by the presence of EURISOL on the same site, since the users would in the main come from other laboratories throughout Europe.

For overall manpower, we can compare the ESS estimate, with 350 persons required, while for the RIA project ANL estimate 253 persons and MSU suggest 320, the latter being the figure preferred by NSAC. This suggests that something like **250 persons** should be adequate for EURISOL, as a 'green-field' stand-alone project, significantly less if located at an existing laboratory.

Note, for example, that the GSI project report explicitly states that it does not include costs for 120 FTE positions 'redirected' from existing posts for the duration of construction, nor for 140 new posts (permanent and temporary) for the design-to-commissioning stages. For the operational stage, GSI has proposed a European Economic Interest Group (EIG) to utilise staff from GSI and other laboratories in Europe.

8.2.5 Conclusion

In general, experience has shown that operational costs per annum for large accelerator facilities are about 10% of the capital cost. The figure thus obtained includes salaries, and would be of the order of 60–65 M€/annum for EURISOL.

9 Conclusions

During the period of the present EURISOL contract, a preliminary design study of the European 'next-generation' Radioactive Ion Beam facility based on the ISOL method has been carried out as far as possible, given the present state of the art in the various techniques involved and the available budget and manpower. We have shown that the calculated yields of exotic nuclides, both purely theoretical and by extrapolation from existing facilities, would indeed be orders of magnitude higher than those currently available. We have compared the yields from ISOL and In-Flight methods, and conclude that the two methods are in fact complementary, underscoring the NuPECC recommendation that Europe should strive to have one of each type of facility.

The report has shown that many previously impossible experiments would immediately be realisable, leading to much-needed knowledge of nuclei beyond the boundaries imposed by the limitations of present-day accelerators. Recommendations are also included concerning directions for future development of detector arrays and instrumentation to optimise the experimental effort with the exotic beams which will become available at such a multi-user facility.

The report also demonstrates that the construction and operation of such an RIB accelerator facility is expected to be quite feasible, with today's technology and some intense R&D in some areas, and that solutions to the remaining problems should readily be achievable. Superconducting RFQ and linear accelerators should then be able to provide the energies and intensities envisaged, with the high transmission efficiencies required, while high-power solid and liquid-metal targets represent a major challenge for development. Thus, the present work is only the first phase of a process, which should include 2 further phases. The second should include Research and Technical Development (RTD) on crucial technical points, which have been identified during the present phase, and which are summarised in Section 7.

The third phase should be devoted to a detailed engineering design of the planned facility, based on the results of the first two phases, and leading eventually to construction of the facility. This will of course require a thorough investigation of the possible sites for building the proposed EURISOL facility, a question which has been deliberately omitted during the present first phase, which was, from the beginning, a site-independent study

In order to carry out the second phase, a proposal for a EURISOL Design Study will be developed and submitted to the European Commission, requesting support under the Design Study part of the Sixth Framework Programme (FP6). This proposal will involve the European laboratories which have participated in the present Feasibility Study, plus a number of other laboratories who have already expressed their willingness to participate in the proposed Design Study. At the same time, the possible synergies of the proposed facilities with other European scientific communities, both at the level of the proposed RTD and also in possible sharing of some parts of the facility with other major projects of these communities, would then be explored in more detail. Of particular interest is the possible use of the EURISOL driver accelerator to produce RIBs which then decay to produce neutrino beams with excellent properties – so-called 'beta beams'. This aspect creates unique opportunities for collaboration between the Nuclear Physics and Particle Physics communities. Numerous applications also exist in other branches of Science, and, as a spin-off, a whole range of Medical applications will become practical with the high yields of exotic radioisotopes produced both on-line and off-line at EURISOL.

The total capital cost of the project is estimated to be of the order of 613 M€, within 20%, as outlined in the body of this report. This sum, while large, is not extravagant when compared to the cost of other large-scale national and multi-national facilities. It is important to emphasise that the EURISOL facility would be a European research facility, and would be intended to serve as a hub for a wide multi-national, multi-user community within and beyond Europe.

We have shown that high-intensity ISOL-produced Radioactive Ion Beams can have exciting prospects for many aspects of science described in this report, including Nuclear Structure at the extremes, Nuclear Astrophysics and Nucleosynthesis, Fundamental Interactions and Symmetry laws. The successful completion of the three phases outlined above, culminating in the construction of the EURISOL facility, would provide the European Nuclear Physics community with the means to maintain a world-leading position in these exciting scientific fields.

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