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NuPECC REPORT

APRIL 2000

The NuPECC Working Group
on Radioactive Nuclear Beam Facilities

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Nuclear Physics European Collaboration Committee
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Preamble by NuPECC

Following one of the recommendations formulated in the NuPECC report of December 1997, "Nuclear Physics in Europe: Highlights and Opportunities," a Working Group on Radioactive Nuclear Beams was established in order to investigate the main options for second-generation radioactive beam facilities in Europe. The general task and the terms of reference for the working group are described in Chapter 1. Initially R. Siemssen (KVI, Groningen, The Netherlands) chaired the group but after Dr Siemssen’s departure to the USA, the chairmanship passed to B. Jonson (Chalmers University of Technology, Göteborg, Sweden). The members of the working group at the different stages since 1997 are also given in Chapter 1. The document presented here reports on the current status and understanding of the field and identifies a number of open questions and options that need further R&D. However, NuPECC took the decision to present this report to the community, as it contains essential information for the large number of R&D programmes which are now devoted to the field of Radioactive Nuclear Beams. NuPECC would like to thank all contributors to this report for their excellent work in providing a report that can form the basis for further discussions within the community.

Decisive moments for the future of the field of radioactive ion beams in Europe are coming:

- several facilities are operational or are reaching the commissioning stage;
- a number of new proposals are in the fundraising phase;
- several European networks addressing the necessary R&D for the next generation of radioactive ion beams have started operating.

Although Europe has taken the lead in this field, severe competition is expected in the near future from North-America and Japan. Europe has the great advantage that many laboratories have devoted their efforts to the production of radioactive ion beams both with the in-flight (IF) method and the ISOL technique. The whole arsenal of different methods of producing radioactive ion beams has been pioneered in Europe and vigorous R&D programmes are being pursued. Also, the detection techniques crucial for conducting successful experiments with these rare beams are the subject of different R&D networks. Last but not least, in the last decade Europe has been at the forefront in conducting pilot experiments with radioactive ion beams ranging from thermal energies through energies in the astrophysical domain up to relativistic energies. This all means that working towards the second generation of radioactive ion beams does not imply a step function where different research groups within Europe are solely orienting their efforts to the project. It rather consists in co-ordinating all the efforts currently going on at many places. The radioactive ion beam community is well equipped to do this, as many R&D projects have obtained EC funding. The major projects are:

- the EURISOL project which aims to conduct a conceptual design study for the second generation of ISOL-based radioactive ion beams
- the R3B (Reaction studies with Relativistic Radioactive ion Beams) project which carries out a similar investigation for the In-Flight method.

These projects are supported by investigations into specific areas of interest:

- the CHARGE BREEDING project aims to develop a fast, efficient and universal way to convert $1^+$ into $n^+$ ions in order to enhance considerably the efficiency of post acceleration;
• the INNOVATIVE ECRIS project is developing ion sources for higher currents, higher efficiencies and higher charge states;

• the EXOTRAP project studies the possibility of manipulating radioactive ion beams by cooling, storing and bunching them in order to prepare them in the optimum way for experiments;

• the EXOTAG project develops the necessary R&D for an efficient and sensitive detection of the products from reactions induced by radioactive beams.

FINUPHY (Frontiers in Nuclear Physics) which is a Concerted Action European programme including the European Research Infrastructures in Nuclear Physics, the R&D programmes and NuPECC, will contribute to keeping the necessary coherence between all these developments.

NuPECC has circulated this status report since it provides an excellent basis for discussions within the Nuclear Physics community. However, NuPECC will also publish separately a short report, for more general circulation including the funding agencies, which will:

• set out the key scientific issues;

• discuss the major technical options, particularly comparing the In Flight and ISOL methods;

• establish a strategy for progress towards future facilities;

• consider the synergy with other areas of science and technology that can develop from a Nuclear Physics proposal.

Lisbon, 25 March 2000
1. Introduction

In December 1997 the Nuclear Physics European Collaboration Committee (NuPECC) issued a report entitled ‘Nuclear Physics in Europe: Highlights and Opportunities’ [1]. One of its themes, and an area signalled for action, was the subject of radioactive beams. This was covered in Chapter 5, ‘Nuclear Structure under Extreme Conditions of Isospin, Mass, Spin and Temperature’, which included the results of a Study Group on Exotic Nuclei and Radioactive Beams. These results had previously been presented to the European Nuclear Structure community at a Town meeting in Orsay in December 1996 and had led to the establishment of a Working Group on Radioactive Nuclear Beam (RNB) facilities in October 1997. The NuPECC report endorsed this group, recommending that ‘A study group should be set up to investigate the main options for second generation radioactive ion beam facilities in Europe’.

The general task of the Working Group, as defined by NuPECC, was to produce a well documented report ‘spelling out clearly the main options for second-generation radioactive-beam facilities in Europe’. Such facilities should aim at RNB intensities 1000 times higher than in the facilities presently running or at the commissioning stage. If more than one is needed to cover the foreseen physics issues, they should be truly complementary. And they should be second to none world-wide. NuPECC’s brief also stipulated that the report should address the needed improvements in the instrumentation used in the experiments so that full benefit of the high intensity can be taken.

1.1 The Report of the Working Group

NuPECC’s terms of reference for the working group state that the report should:

- choose a few burning physics issues and derive from them the required properties expected from the second generation RNB facilities;
- contain a detailed comparison of the different production methods, ISOL or In Flight, and of the relative merits of high-energy protons, heavy ions, slow neutrons and fast neutrons as incident beams to produce intense secondary RNBs;
- consider in detail the post-acceleration of RNBs including charge amplification, storage rings and other auxiliary equipment;
- compare the potential European facilities with those under construction or planned world-wide.

This report presents the position reached by the Working Group at the end of 1999 towards achieving these objectives. A detailed survey of the various possible options for second generation RNB facilities has been carried out and a few recommendations are put forward.

1.2 The Way Forward

The two methods used in RNB facilities to produce beams are substantially different. One is commonly called Isotope Separation On Line (ISOL) and the other is called In Flight. In
an ISOL-type facility, radioactive nuclei are produced essentially at rest in a thick target, catcher or gas cell bombarded with particles from a primary source or driver accelerator. After ionisation and selection of a specific mass by electromagnetic devices, these nuclei are accelerated in a post-accelerator. For the in-flight method, an energetic heavy-ion beam is fragmented while passing through a thin target, and the reaction products are subsequently transported to a secondary target after mass, charge and momentum selection in a fragment separator. Since the reaction products are generated in flight, no post-acceleration is required. The two methods are entirely complementary. While ISOL facilities allow good quality low energy RNBS to be produced, in-flight facilities are optimum for higher energy beams of very short-lived nuclei. Both types of facility are necessary for pursuing the scientific goals of the nuclear physics community, as will be substantiated in this report.

It is clear that, if an ISOL facility that can deliver beams a factor 1000 more intense than anything currently planned is to be built, then considerable development work is needed. Identification of the work required and its execution will be the next task. This will be facilitated by the support of the European Union (EU) for some RTD projects which became operational at the beginning of the year 2000. These are:

- **EURISOL** - A preliminary design study of the next-generation European ISOL Radioactive Nuclear Beam Facility. This project will include nine European laboratories and last two years with an EU budget of 1.5 Meuro;

- **CHARGE BREEDING** - Charge Breeding of Intense radioactive beams. This project will include seven European laboratories and last three years with an EU budget of 1.2 Meuro;

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

- **EXOTAG** - Studies of Exotic Nuclei using Tagging Spectrometers. This project will include eight European laboratories and last four years with an EU budget of 1.5 Meuro.

These projects are clearly in line with the tasks of the Working Group, which actually initiated the first three, and which will closely follow and co-ordinate their progress.

### 1.2.1 Outline of the report

The present report includes four main chapters followed by a conclusion.

**RNB Lessons and Challenges.**
This chapter presents a general survey of the science that is addressed by RNB facilities with an emphasis on the fast-developing theoretical aspects, which are of benefit to the whole field.

**Present world-wide situation of Radioactive Beam Facilities.**
This chapter reviews the present status of RNB Facilities world-wide whether they be operating, at the commissioning stage, approved and under construction, or proposed.

**ISOL Facilities.**
This chapter includes a thorough discussion of the different target-ion-sources that may be used to produce high yields of very exotic, isobarically pure nuclei to be post-accelerated in an ISOL RNB facility. It also discusses the various possible options for the post-accelerator in an ISOL RNB facility, including charge breeding of the ions to be post-accelerated and major special instrumentation to be used.

**In-flight Facilities: Physics with Exotic Nuclear Beams.**
This chapter presents the main options for a European next-generation in-flight facility and some experimental tools to be constructed at such a facility, in particular storage and cooler rings. Some parts of this chapter also apply to ISOL facilities, for example, stopping in gas cells.
Table 1.1:


Table 1.2:

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<th>Members of the Working Group December 1998 onwards</th>
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<td>A.C. Mueller (Vice Chairman)</td>
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<td>J. Vervier</td>
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<td>G.-E. Körner (Scientific Secretary of NuPECC)</td>
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1. Introduction
2. RNB Lessons and Challenges

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

This chapter opens with a short introduction to the field of Radioactive Nuclear Beams (RNB\textsuperscript{1}) that covers nuclei from the line of beta-stability to the limits of nuclear stability and beams from essentially zero energy to more than 1 GeV/u. A section with some selected examples of recent highlights in the field is followed by a longer account of the present status of theoretical understanding. At the end connections to nuclear astrophysics and to other scientific fields are mentioned.

2.1 The Many Facets of Nucleonic Matter

The study of unstable nuclei encompasses new aspects of \textit{nucleonic matter}. The atomic nucleus is a collection of interacting nucleons, a quantal many-body system where various characteristic degrees of freedom emerge and have been discovered. Whenever new experimental techniques for accelerating and/or detecting particles have been developed, new and often unexpected features have shown up. In this respect it is of the utmost importance for the nuclear physics community to invest in new apparatus, for example accelerators, detector systems, data acquisition methods and computing power, to explore the extremes of stability by heating the nucleus (temperature degree of freedom), by bringing angular momentum to the nucleus (extremely rapid rotating nuclei) and by forming very proton or neutron-rich nuclei (approaching and mapping the dripline regions). With access to exotic nuclei at the very limits of nuclear stability the edges of the nuclear landscape can be explored. At these limits, the neutron and proton \textit{driplines}, additional neutrons or protons can no longer be kept in the nucleus - they literally drip out. The exact locations of the boundaries are far from clear and their complete delineation awaits a better quantitative understanding of the nuclear system.

Nuclei far from stability allow us to amplify and isolate particular aspects of the nuclear interaction and dynamics. Future work will involve, for example, investigating neutron halo systems, mapping the neutron dripline further up, learning about the astrophysical rp- and r-process paths, exploring the evolution of shell structure and neutron skins, creating further superheavy nuclei, studying super-allowed beta-decay in very light proton rich nuclei, developing a deeper understanding of proton-neutron pairing and studying the exotic phenomenon of proton radioactivity. We are presently at a stage where particularly interesting nuclei, such as the most recently seen “double-magic” nuclei, can be produced with intensities of one per day to one per week. This gives us a first glimpse of the physics that we can learn here, but we need intensities to increase by several orders of magnitude before real physics explorations can begin.

Figure 2.1 shows a map of the nuclear landscape. We believe there is only a limited number of nuclei that can exist. Of these about half have been seen in the laboratory but only a small number exist naturally on Earth, these

\textsuperscript{1}The acronyms RNB, RIB (Radioactive Ion Beams) and RIA (Rare Isotope Acceleration) are used for this field.
are marked by black squares. The magic numbers, associated with increased stability, are the convenient “landmarks” in the map and are indicated by double lines. Also shown are estimates of the borderlines of stability, the so-called driplines, and two of the paths astrophysicists have found to be important in the creation of elements in the Universe: the r-process and rp-process paths. A third path, the s-process path, runs along the stable nuclei. The r- and rp-process paths shown traverse regions as yet unexplored and there is also important nuclear physics waiting beyond nuclear astrophysics. Proton-radioactivity beyond the proton dripline, the superheavy nuclei corresponding to new elements and new structures appearing on the way to and at the neutron dripline are a few examples. We need experimental access to presently unexplored regions to make further progress and refine our theoretical understanding.

2.2 RNB Discoveries

The complexity of the nuclear many-body problem, for which the interaction between the nucleonic constituents still is not fully settled, has made nuclear physics a phenomena-driven field. The study of nuclei has through the years revealed a rich variety of genuine nuclear phenomena and dynamics. Remarkable discoveries have already been made with radioactive nuclear beams, some will be discussed in the following sections.

2.2.1 Halos - dilute nucleonic matter

The neutron dripline has so far been reached for light nuclei, leading to a rich vein of research possibilities. Triggered by the discovery in 1985 of vastly spatially extended nuclei ($^6\text{He}$, $^{11}\text{Li}$, $^{11}\text{Be}$) at the neutron dripline, the initial idea of binary halos was suggested. Subsequent developments have deepened and enriched the picture of halos as a new structural dripline phenomenon with clusterization into an ordinary core nucleus and a number of halo nucleons forming very dilute neutron matter. The origin of these structures is of pure quantum mechanical nature and only partly understood. A prerequisite, however, is low angular momentum motion for the halo particles and few-body dynamics such as in Borromean nuclei\(^2\) charac-
terized by pair-wise constituents with no bound states. In the limit of vanishing binding, extremely large halos may occur.

Halos have mainly been seen in ground states of light nuclei (Fig. 2.2). The best known one-neutron halo nucleus is $^{11}$Be, but recently $^{19}$C has also been studied. Among two-neutron halo nuclei, the best established ones are $^6$He and $^{11}$Li, but indications for halos in heavier systems also exist. There are also candidates for proton-halo nuclei, the best explored one-proton candidate being $^8$B, famous for its role as a solar neutrino source. Most of the detailed experimental information we have on halo structure is obtained in break-up reactions at intermediate and high energies.

The irregular behaviour of the $1s_{1/2}$ orbit, intruding into the $p$-shell, was noticed quite early in $^{11}$Be. It is an important element in our understanding of lighter dripline nuclei and is also believed to play a role for the structure of the two-neutron halo in $^{11}$Li, shown in Fig. 2.3. The detailed experimental information we have on halo structure is obtained from break-up reaction and beta-decay experiments.

Figure 2.2: The size and granularity of the most studied halo nucleus, $^{11}$Li. The matter distribution extends very far out such that the RMS matter radius of $^{11}$Li is as large as that of $^{48}$Ca, and the radius of the halo neutrons as large as for the outermost neutrons in $^{208}$Pb. It is a challenge for theory to account for both the extension and the granularity.

The angular distribution between $^9$Li and a neutron recorded following break-up of $^{11}$Li on a C target. The data were taken at 287 MeV/u at GSI. The skew distribution is a signal of the existence of both s- and p-wave components in the final state and can be used for a quantitative measurement of the contribution of these two angular momentum components in the $^{11}$Li wavefunction.

![Angular distribution](image)

Figure 2.3: The angular distribution between $^9$Li and a neutron recorded following break-up of $^{11}$Li on a C target. The data were taken at 287 MeV/u at GSI. The skew distribution is a signal of the existence of both s- and p-wave components in the final state and can be used for a quantitative measurement of the contribution of these two angular momentum components in the $^{11}$Li wavefunction.

The theoretical description of dripline nuclei is an exciting challenge. The coupling between bound states and the continuum asks for a strong interplay between various aspects of nuclear structure and reaction theory. This theoretical effort must be supplemented by experiments giving improved data on existing nuclei and, in particular, data on new halo nuclei. Isospin and charge symmetries in the context of halo nuclei have also been examined, in particular in connection with $\beta$-decay experiments.

### 2.2.2 Beyond the driplines

Even though nuclei beyond the driplines are unbound against particle emission they might exist as resonances and may therefore be studied experimentally, in particular at the proton dripline.
where the Coulomb barrier retards particle emission. Very short-lived nuclei have also recently been observed for light nuclei. The cases studied include $^{7,9,10}$He, $^{10}$Li, $^{13}$Be, $^{11}$N and $^{12}$O. The structure of nuclei just beyond the dripline is very often strongly related to that of nuclei that are just bound, an important example being that of Borromean nuclei, and the information obtained from them is therefore often crucial in tests of theoretical understanding.

Ground state proton radioactivity has been known for some time but recent experimental progress has yielded much more data which is also of a more systematic nature. There are almost 30 known cases of proton radioactivity for $Z > 50$, from $^{105}$Sb ($E_p = 0.478$ MeV) to $^{185m}$Bi ($E_p = 1.585$ MeV). Proton decay out of resonant states, confined on the Coulomb barrier but otherwise unbound, has been studied in both heavy spherical and medium-heavy nuclei indicating a new region of quadrupole deformed shapes. Gamma-ray cascades in these unbound nuclei have even been observed by making use of ingenious techniques combining fragment mass analyses (FMA or RMS) with proton-decay tagging methods. The related two-proton radioactivity is still unobserved, although two-proton emission from excited states and broad resonances in light nuclei is known.

Theoretically, the physics of nuclei with very large values of neutron or proton excess is a challenge for well-established models of nuclear structure and, because of the limitations involved when extrapolating, it invites novel theoretical approaches in which the stability criteria for nuclei with extreme neutron-to-proton ratios are studied in a general way using existence theorems; much as is done in atomic and molecular physics. Since the parameters of interactions used in the usual shell-model or mean-field calculations are determined so as to reproduce the properties of known nuclei, the parameters may not always be appropriate for use in the calculations of dripline nuclei. We expect, however, that the spectroscopy of exotic nuclei by means of RNB techniques will lead to a better determination of forces, at least those interaction components that depend on the isospin degree of freedom.

### 2.2.3 Confirming closed shells and melting closed shells

A sense of paradox surrounded the development of the nuclear shell model (SM) 50 years ago, a sense that is preserved in the early reference to the closed shells as “magic numbers”. A quarter of a century later some of the mystery still persisted, and Elisabeth Urey Baranger opened her jubilee article in Physics Today on the status of the nuclear shell model with the line ‘Useful though the shell model undoubtedly is for providing a correlation of the structure and properties of nuclei, theorists are still wondering why it works’.

Whereas in the early phases very restricted model spaces and simple schematic forces were used, state-of-the-art shell-model calculations have reached very big dimensional spaces and use well-determined effective interactions or start, on a more basic level, from realistic G-matrix descriptions of the underlying two-body forces.

Since then new closed shell nuclei have also been reached and explored. These include $^{100}$Sn near the proton dripline and the neutron rich $^{132}$Sn, a doubly closed $Z=50$, $N=82$ nucleus which may become a reference point as important as $^{208}$Pb. Recently $^{48}$Ni and $^{78}$Ni have also been observed at GANIL and GSI respectively, but in very limited numbers. Evidence for shell ordering at the neutron dripline which differs from that we are accustomed to is now, however, appearing. There are theoretical indications that nuclei with a large neutron excess would have a potential with a softer fall-off than the one in a Woods-Saxon potential, thereby influencing the ordering of orbits. On the experimental side the N=20 nuclei have been studied in considerable detail, the closed shell still persists in $^{34}$Si but is clearly gone in $^{38}$Mg and $^{31}$Na. State of the art shell-model calculations reproduce this.

### 2.2.4 The heaviest nuclei

The predictions in 1966 of magic numbers $Z=114$ and $N=184$ gave rise to expectations of the existence of an island of unusually long-lived
neutron rich superheavy nuclei, well out in the uncharted sea of instability. It is only a few years since the elements with atomic number $Z=110-112$ were produced for the first time at GSI. Recently JINR at Dubna have found evidence for the shore of this island by colliding $^{48}$Ca and $^{244}$Pu with enough energy to overcome the mutual electrostatic repulsion. Evaporation of three neutrons proved to be a sufficient cooling mechanism of the compound system to bring the resulting element $Z=114$, $N=175$ below the fission barrier, resulting in a half-life of 30.4 seconds. In subsequent studies at the mass separator at the Lawrence Berkeley National Laboratory (LBNL) using the reaction $^{86}$Kr on $^{208}$Pb, indications of elements with atomic number $Z=118$ and mass $A=293$ have been recognized by a sequence of very specific alpha decay chains. These recent discoveries are very important indicators of the presence of shell structure in these very heavy elements, corroborating the long-predicted idea of an island of stability for superheavy elements.

We do not yet have a definite prediction of the position of the closed spherical proton shell in this island of stability, different theoretical approaches point to $Z=114$ or $Z=126$. New experimental data, in particular on more neutron-rich heavy elements, are needed to build up a better picture of the nuclear structure in this region.

2.2.5 New experimental techniques

Much of the progress mentioned above has depended on the development of new experimental techniques for the production of radioactive beams, new techniques for their detection, or both. During the last decade the limits of known nuclei have been pushed further so that the proton drip line now is reached in many places and the neutron drip line is believed to be known up to about Ne.

Studies of high-energy secondary beams started at LBNL’s Bevalac and have been continued both at intermediate and high energies. Storage and cooling techniques have been developed, largely at GSI, and measurements using traps have been performed in several places, starting with ISOLDE. The first steps towards the post-acceleration of ISOL-beams have also been taken. Concurrently with these developments important improvements in detection systems, following the trend in particle physics of moving towards large solid angles and high granularity, have also been made. These are crucial in the RNB case due to the low intensities of the secondary beams and also because complete coverage allows correlation measurements between all emitted particles to be made. This in turn permits important physics questions to be addressed more directly than with conventional methods.

To give an example from a field not so far touched upon, large gamma-detection arrays developed in the last 10 years have opened up the possibility of observing the full $4\pi$ solid angle of detection. By combining a number of techniques including Ge detectors with Compton suppression, simultaneous detection of particles emitted in nuclear reactions (tagging), mass analyzing techniques such as fragment mass analysers and recoil mass separators, and electronic advances in multiple-coincidence detectors, a number of unique tools for studying nuclear phenomena have been made. These have permitted, for example, the observation of rotational bands at high nuclear spin and high excitation energy. Superdeformed, and possibly also hyperdeformed, shapes have been detected and mapped out systematically in the rare-earth region, near the Pb closed shell and also in the mass $A=100$ region. Future RNB techniques will eventually allow these studies to be extended. Such methods have also been used in mapping out nuclear structure of very neutron deficient nuclei in the Pb region thereby stumbling on unexpected forms of shape coexistence. Recent experiments at Jyväskylä and Argonne have investigated the structure of nuclei with $Z > 102$ for rotational bands up to $18h$, for example $^{252,254}$No.

2.2.6 Identification of key observables and experiments

How deeply can we probe the spatial and structural characteristics of exotic nuclei? To what extent can few-body features and core prop-
erties be discriminated in exclusive/complete experiments? These are important questions since most theoretical “observables” in quantum physics are not directly accessible to experiment. This applies even to large scale geometrical characteristics such as rms radii. Consequently it is not clear that procedures and standard reaction theory tested for stable nuclei apply at the driplines. The interplay between structure and reactions is now attracting increasing attention, and the important content in increasingly more exclusive observables is a future challenge. Safe progress certainly requires realistic treatments of the relevant degrees of freedom of the constituents taking the spatial granularity — cluster structure of the collision partners — into account. Promising studies of (transfer) reactions that ‘filter’ exotic structural features, such as di-neutron configurations, have already been initiated. The influence of the structure of the nearby continuum also makes reactions with loosely bound nuclei a tool for advancing fundamental reaction theory.

2.3 Current Theoretical Understanding

This section gives an overview of the present theoretical status of the field. An introductory subsection is followed by accounts of few-body models, mean-field models and shell-models. The section ends with an account of the role played by symmetries in our understanding of nuclear systems.

2.3.1 The nuclear many-body problem: a short introduction

To show how progress within nuclear structure theory can be made it is useful to look at the various levels at which one can attempt to understand nuclear phenomena, as illustrated in Fig. 2.4.

There is an overall effort to explain the higher levels in Fig. 2.4 in terms of lower ones but a complete reductionistic “deductive approach” is unlikely to be the most efficient way of understanding nuclei. Moreover, this can not yet be technically done. A more constructive physical approach is to isolate and understand the effective degrees of freedom of nuclei. Progress can be made, and is needed, on all levels. In general terms the goal of radioactive beams is to provide more experimental data — to add to the top level. But these data should be qualitatively new and on new phenomena rather than refine older experiments. This will enable better tests of nuclear models on the lower levels and allow real progress in improving overall understanding.

Figure 2.4: Different levels in the (theoretical) understanding of nuclei. A new generation of RNB facilities will add information on the top layers thereby making possible improved tests of our understanding of the nuclear many-body problem.

2.3.2 Nucleon-nucleon forces at work

The nucleus is a typical example of a self-organized system, in contrast to atoms in which electronic motion is largely dictated by Coulomb interaction with the atomic nucleus.

An improved understanding of the effective nuclear interaction is a major goal of the contemporary theory of systems of strongly interacting hadrons. The effective nucleon-nucleon interaction can, in principle, be derived from the bare nucleon-nucleon force. Compared to the free nucleon-nucleon interaction of two particles, which can be fairly well determined from
scattering experiments, the effective interaction must include the following three physical effects:

- Existence of a hard core, which cannot be treated approximately but should be described by solving the two-particle problem exactly.
- Modification of the interaction by the medium of nucleons in which it occurs.
- Reduction in the phase space used for the description of many-nucleon states, the Pauli-quenching effect.

There has recently been renewed interest in studying the properties of effective interactions from first principles but much more effort is still needed. In many practical applications phenomenological effective interactions fitted to experimental data are used. Such approaches are very successful, showing that the concept of an effective interaction applies very well to atomic nuclei. In particular, we may use the effective interaction either in the mean-field approximation or in shell-model diagonalizations (see Subsections 2.3.4 and 2.3.5). The former is an approximate, variational, method which has the advantage of being able to use large configuration spaces, in particular the co-ordinate representation for nucleon wave functions, and it can be applied to very heavy nuclei. The latter requires a strong reduction of the single-particle model space but it allows exact solutions in light nuclei, both for the ground and excited states.

The strong links which exist at present between experiment and the approaches using effective interactions call for an extension of the study of nuclei far from stability. This is in fact one way to establish the properties of the effective interactions. Applying effective interactions to nuclei near the stability valley allows a consistency test, which then allows predictions to be made for nuclei still further away from stability. The challenge is to deal with issues which pertain to studies of nucleonic systems far from stability, at high excitation energies and at high angular momentum.

At present, we do not actually ‘see’ the nucleons in their single particle motion, but can obtain a glimpse by studying processes where nucleons are either extracted from or deposited into a nucleus. Other key experiments have, for example, been carried out by measuring the charge density difference in electron scattering from $^{208}$Pb and $^{209}$Tl, and from the momentum distribution derived from $(e,e'p)$ reactions on light nuclei. What is really involved is not exactly the orbits in a shell-model potential, but a model independent translation invariant quantity, namely the overlap between the states of the A and A+1 (or A-1) systems being connected by the transfer process. Due to absorption in hadronic processes, the region where information is extracted is shifted to the nuclear surface and the tail part of the overlaps. It was shown quite early that one-neutron overlap functions decay exponentially with a decay constant governed by the separation energy of the two states being connected. This gave rise to the so-called well-depth recipe where harmonic oscillator wave functions were replaced by Woods-Saxon wave functions with correct separation energy and appropriate quantum numbers. The various Woods-Saxon orbits no more belong, however, to a common potential well depth.

As far as the positioning of nuclear driplines is concerned, it is not the absolute value of the nuclear mass but rather the mass difference between two isotopes that is of interest. The difference between binding energies, $B(Z,N)$, determines both the one-neutron separation energy $S_n(Z,N) = B_n(Z,N) - B_n(Z,N - 1)$, and the two-neutron separation energy, $S_{2n}(Z,N) = B_n(Z,N) - B_{2n}(Z,N - 2)$. If $S_n$ becomes negative, then a nucleus is neutron unstable; the condition $S_{2n} = 0$ determines the position of the one-neutron dripline. By the same token, if $S_{2n}$ becomes negative, a nucleus is unstable against the emission of two neutrons; the condition $S_{2n} = 0$ determines the position of the two-neutron dripline. Proton driplines are defined in a similar fashion. Because of their sensitivity to various theoretical details, predicted driplines are strongly model dependent. The variations between predictions can be attributed to three factors: fundamental differences between microscopic approaches, different effective interac-
tions employed within the same approach, and different approximations used when solving the nuclear many-body problem within a given approach.

The role of overlaps as basic building blocks is now being readdressed, as is their role for no-core calculations of light nuclei, which will be discussed below. Within an F-body model for a halo nucleus (F=1,2,...), the wave functions that are calculated are just F-body overlaps.

2.3.3 Few-body perspectives

In studying light systems composed of just a few nucleons, the nucleon-nucleon force could be used as the key to a very ambitious programme of determining nuclear properties using variational methods. These methods, Variational Monte-Carlo (VMC) and Green’s Function Monte-Carlo (GFMC), have provided the first fully microscopic calculations that directly reproduce nuclear shell-structure from realistic interactions. With the aim of studying very light and few-nucleon systems, another line of approach is the large-basis no-core shell-model (LBSM), which tries to demonstrate that the shell-model combined with a microscopic effective interaction is capable of providing good agreement with the experimental properties of ground-state and low-lying excited states. The GFMC method is, however, more ambitious. Neither GFMC nor LBSM are so far able to “generate” loosely bound halo systems such as $^6$He and $^8$He, missing by several MeV. Comparing calculated continuum spectra for the unbound $^7$He nucleus, for example, the LBSM gives a spectrum with a much less compressed form.

The size of the GFMC and LBSM calculations regrettably grows beyond what is manageable even before nuclei like $^{11}$Li are reached. Nevertheless, some very useful lessons have been learned from these pioneering attempts. The GFMC calculations for the mass A=6 system, for example, do reproduce an alpha-like core object. For mass A=8 and 10 systems on the other hand, the LBSM is hampered by the use of shell-model single-particle wave functions with incorrect asymptotics. Thus, the shell model when used in this way does not seem suitable for the description of weakly bound states or resonances. Elucidating this situation is, however, very much what dripline physics is all about.

Work is being carried out in order to explore means to combine auxiliary and diffusion Monte-Carlo methods which could point to a consistent way to bridge the gap between very few-body systems and light nuclei. Pioneering activities usually employ some kind of scaffolding and the discoveries are highlighted in terms of heuristic interpretations. These emphasize new findings. Halo physics is no exception. The binary core, a dineutron picture for two-neutron halos was originally just meant to illustrate how large extension and weak binding may be related. It is possible, however, to explore few-body characteristics that have an overwhelming influence on the precise nuclear structure properties for light nuclei (beyond mass A=8) by explicitly building up such systems using binary and more complicated cluster structures. Since 1990 halo models have been developed where the N-N degree of freedom is no longer frozen but chosen in accordance with the free N-N interaction inspired by the dilute character of the halo. Focus has thus been shifted to features genuinely related to the intrinsic character of the halo and the interplay of halo degrees of freedom.

The picture of a “normal” nucleus embedded in a neutron halo, in other words the coexistence of normal and low density nuclear material, has emerged from a concerted effort between dedicated measurements and theory. Few-body dynamics plays the crucial role in any adequate description of halo properties since for halo bound states most of the wave function is concentrated in the classically forbidden region. The chain of He isotopes with an alpha core has become particularly useful as a benchmark system.

Dripline physics with nuclei having only one or a few weakly bound states is the physics of threshold phenomena where structure and reaction theory merge. Recently theorists have addressed this issue and successfully extended the theoretical few-body approach to encompass three-body continuum structure, response func-
tions and reactions involving Borromean systems. For the first time it has been demonstrated how even inclusive observables such as diffractive break-up are intimately related to the structure of the three-body continuum. The measurement and analysis of the continuum response of halo systems near threshold directly explores this asymptotic behaviour. This development is also enabling us to understand the physical nature of the famous “soft modes”, present in the low-lying continuum of neutron-rich lighter nuclei.

Very extended spatial correlations in the three-body Borromean continuum are found within a full three-body dynamical model. Correlated spatial densities for antisymmetrized plane waves, for narrow 3-body resonances as well as densities for wide resonances, and for 3-body-virtual excitations are currently being analysed.

A dream dating back to the early years of nuclear physics is that of starting from the free nucleon-nucleon two-body interactions to build up a framework for reaction processes as well as the study of bound nuclear structure properties. The influence of the nuclear medium has complicated this approach. For loosely bound dripline nuclei, however, it is once more in fashion for learning about three-body forces and reaction mechanisms.

The nature of the halo seems sufficiently dilute to justify approaches where the starting point is the free nucleon-nucleon t-matrix. Work has therefore begun on charge exchange at higher energies within multiple scattering formalisms. In addition, few-body reaction theories that are particularly appropriate to heavier halo candidates are being developed.

2.3.4 Mean-field methods: accomplishments and limitations

Mean fields in the atomic nucleus can be determined and studied using Hartree-Fock-Bogoliubov (HFB) methods. The effective interaction in heavier nuclei is strongly affected by in-medium effects, much like the effective interaction between electrons in solids. Theoretically, the in-medium modification of the nucleon-nucleon force can be carried out using the Brueckner method (G-matrix theory). Although significant progress in the effective interaction theory has been made during recent years, the currently used strategy is to use density dependent effective forces. In calculations over many years, zero-range forces, velocity-dependent Skyrme forces and finite range Gogny forces have been successfully used to determine various nuclear properties. The non-relativistic Skyrme-HFB models have their roots in the local density approximation and the energy-density functional. The relativistic mean field (RMF) theory is based on self-consistent coupling between baryons and mesonic fields. Pairing correlations are usually included in a Bogoliubov framework (RHB-Relativistic Hartree Bogoliubov extension).

In the self-consistent approaches, the nucleonic single-particle and pair densities are obtained from the eigenstates of the HFB or RHB eigenvalue problems. The mean-field Hamiltonian depends on these densities, hence the corresponding equations are strongly nonlinear.

Because the proton-neutron attraction is the dominant part of the effective nucleon-nucleon interaction, the neutron mean field depends most strongly on the proton density and vice-versa. As a consequence, for nuclei with an extreme neutron excess and increased neutron density in the surface region, the neutron mean field in this outer region becomes weak while in the nuclear central part, the neutron mean field is strong and determined by the local proton density. These opposing tendencies in the radial structure of the neutron mean field will make up for a more complicated field compared to the nuclei in the region near stability. In other words, one needs to pin down the isovector density as precisely as possible.

These observations will most probably cause a division between a central and a surface region to cease, allowing a more gradual decrease of the neutron average potential from the central zone in the nucleus towards large radial values to show up. This can have drastic effects on the precise nuclear shell-structure that in turn de-
terminals the filling of orbitals and thus of the nuclear densities, making self-consistency arguments very important.

An essential building block of mean field methods is the pairing field. Nuclear superconductivity becomes extremely important for weakly bound nuclei since the particle continuum forms an infinite reservoir of states accessible to scattering of nucleonic pairs. Consequently, the coupling between mean fields, pairing fields and the particle continuum is very strong in such systems.

It is therefore of the utmost importance to map out the single-particle structure while progressively producing more neutron-rich nuclei for light, medium-heavy and heavy systems. The study and production of odd-mass nuclei, far from stability, and the study of beta-decay that gives access to the precise underlying shell-structure is also extremely important when drawing up RNB proposals and experiments. Examples include approaching the $^{78}$Ni region and producing very neutron-rich nuclei around $N=28$.

The whole issue becomes complicated by the fact that while approaching the very neutron-rich regions, a low-density region, saturated mainly with neutrons, might be reached forming systems that are barely bound. The HFB and RHB methods provide a framework for dealing with the complexities that arise. For very neutron-rich nuclei, weak binding and strong pairing correlations give rise to very diffuse mean fields. The resulting shell structure is predicted to differ from that known in nuclei close to the beta-stability line. Some Skyrme-models, for example, predict quenching of magic gaps, resulting in a more uniform single-particle spectrum. In the RMF theory, strong reduction of the spin-orbit splitting is predicted. One of the main goals of RNB physics is to investigate the shell structure of neutron-rich nuclei to learn more about the NN-interaction in heavier nuclei. The pairing field that scatters pairs of nucleons in weakly-bound systems such that continuum effects will start playing an important role is at present only partly known. Simple extrapolations from known regions near stability can not be expected to converge to the correct answers to this question.

One can envisage the possibility that specific clustering may lower the energy of an interacting many-body system when extreme neutron-to-proton ratios are reached. And that deformation in the weakly-bound surface zone with respect to the more strongly bound central region may result in soft electric dipole modes, new scissor-types of motion and, as has been discovered in the one-proton emitting region, probable zones of bound configurations embedded in an unbound region of instability, much like the original study of BSEC-structures. Here the organization of the nuclear many-body system in minimizing its energy will certainly reveal surprises along the way from the region at or near to beta-stable nuclei with near equal distribution of protons and neutrons over single-particle states into the extremes of instability with a big neutron (or proton) excess. As for light nuclei, theoretical studies of “existence” theorems concentrating on the derivation of binding conditions for general A-body systems, assuming no bound subsystems exist, may become useful. In this respect the use of model systems and schematic forces that lead to exactly solvable systems may well form a first step into the genuine exploration of dripline regions. The creation of new technical means is essential in making this journey as daring as possible.

2.3.5 The nuclear shell model at work

Large-scale shell-model studies

Modern large-scale shell-model calculations try to incorporate many or all of the possible ways in which nucleons can be distributed over the available single-particle orbitals, which are fairly well fixed for a given mass region. The current shell-model codes can cover these regions as $1\hbar\omega$ model spaces fully without any need for model truncations. The effective forces used are optimized with respect to this particular full model space.
Adding to calculations in the full p and sd shells, the full fp shell nuclei have more recently been studied in considerable detail using large-scale shell-model codes. These codes have been developed over the last two decades to contain state-of-the-art technical capabilities. At present, issues like the shell closure in $^{56}$Ni and related topics can be studied in a much better way than before.

There are a number of questions, however, that are connected to moving far out from the region of beta-stability. These relate in particular to building huge model spaces within a given $1\hbar\omega$ model space with dimensions reaching $10^9$, leaving the underlying core as an inert system. Experimental data further away from stability have pointed out serious deviations from the results obtained from these large-scale shell-model studies. The N=20 nuclei, for example, including Na and Mg are a case in point. Moreover, in keeping with the very big “linear” way of model space building, unexpected ways for the nucleons to become organized can bring up new physics even at very low energies. Here, we think of the already large amount of experimental data indicating that a new class of states can “intrude” to low energy thereby bringing in new physics from outside the lowest-order shell-model truncation. Examples are most dramatically available in the very neutron deficient nuclei in the Pb region, and for light very neutron-rich N=20 and N=28 nuclei.

It has become clear that a simple “linear” growth of such approaches is likely to run into limitations. We should not see this as a drawback but as an interesting indicator that new physics is showing up. For example, if we use the spherical shell-model as fully as possible in a given mass region and encounter serious and systematic deviations between experiment and theory, we can take this as a fingerprint for new physics. This argument is particularly important in carrying out systematic calculations when entering the unknown territory of nuclei far from stability. It was, after all, the data on two-neutron separation energies, $S_{2n}$, in the N=20 region that brought the information needed in order to outline a new zone of deformation around the Mg ($Z=12$) isotopes, connected to a break-up of the standard neutron shell-closure at N=20.

**Truncation methods**

While optimizing the model space to the physics present (low multipole field producing quadrupole and octupole correlations or high-multipole and pair scattering processes that favour spherical density distributions for example) we normally try to match the effective forces acting amongst the nucleons with an optimized truncation of the huge and frequently intractable shell-model configuration spaces. This truncation plays an essential role in capturing the physics of the nuclear many-body problem, so one should not look at the truncation process as a mere way of “model building” but more as trying to concentrate on the essential degrees of freedom that show up when nucleons are left “free” while interacting inside the atomic nucleus.

Our aim is not to study and describe the large number of specific truncation methods but to stress the importance of building up robust truncation methods that could allow meaningful extrapolations outside the region of stability.

A particularly promising way of truncating nucleons interacting in nuclei considers the possibility that molecular structures or more general cluster-like systems could develop. This will be particularly important when entering new ground far from stability.

**Monte-Carlo shell-model methods**

A central element in the study of atomic nuclei, and one that will be a focus of the new RNB facilities, is related to the question of how the nucleus will modify its underlying structure when some of the external parameters are changed. How will the concepts of a central field and the derived properties change when heating the nucleus to a temperature corresponding to stellar conditions, when bringing in a very large amount of angular momentum or when changing the proton and neutron densities in a major way compared with nuclei near stability? Temperature, angular momentum and the proton-neutron asymmetry are essential properties that are common to all physical systems.
A formalism that puts temperature back into a central place (and similarly angular momentum as well as the proton-neutron assembly) may well form a powerful new method. At these higher energies, and most probably also for very high angular momentum and very special proton-to-neutron ratios, it is almost impossible in principle to follow all the individual nucleons in the interacting nuclear many-body system. Very much as statistical averages build a bridge between microscopic and macroscopic variables (average particle velocity distribution on the one hand and pressure, temperature and other macroscopic variables on the other), we may concentrate on the thermodynamics of the atomic nucleus in order to learn more about its behaviour.

Shell-model Monte-Carlo methods (SMMC) have been developed to a high level of sophistication in order to determine the nuclear partition function and derived quantities such as sum rules for various external fields interacting with a heated atomic nucleus. There may well be ways to use some of the essential elements of the SMMC methods in order to derive the analogous “classical observables” that will appear in systems at rapid rotation and for systems far from stability, or to combine any of those elements in a very general way. This is almost uncharted territory to be entered in the coming years.

2.3.6 Symmetries and the nuclear many-body problem

Because of the strong binding forces acting inside the atomic nucleus, the nucleons appear very much as if they formed a liquid drop that is able to undergo dynamical fluctuations around a spherical or a deformed shape. This gives rise to what are called structural symmetries of the atomic nucleus. The nuclear binding forces themselves exhibit a number of symmetries that subsequently give rise to symmetries within the interacting nucleon system. These can, under certain conditions and in given mass regions, give rise to the exhibition of dynamical symmetries.

The concept of symmetries, as a central theme in the discussion of a large variety of physical systems, has given deep insight into the interrelationships between various domains of physics. Dynamical symmetry concepts have been a guiding idea in nuclear physics over the years. In Fig. 2.5 we outline the way symmetries have helped to elucidate the salient features of the nuclear many-body system. Examples cover isospin in nuclei, Wigner supermultiplet symmetry, the symmetries related to the harmonic oscillator motion and, more recently, the dynamical symmetries related to nuclear quadrupole collective motion. They also indicate the importance of exploring such concepts for many-body systems far from stability.

![Symmetry Diagram](image)

Figure 2.5: A brief illustration of the history of important symmetry ideas in nuclear physics.

In producing neutron-rich nuclear matter, the translational symmetries of infinite matter will show up as the limiting case. By systematically breaking such symmetries through building in specific localized cluster structures that distort this original symmetry (chains of alpha-clusters, di- or multi-nucleon components or hitherto unknown types of correlations) be-
fore reaching the totally opposed system of individual nucleons, a rich playground of nuclear correlated structures can appear. Therefore, open-minded efforts to map the vast space between stable nuclei and the driplines using RNB methods and facilities will form a central issue in basic research in forthcoming years. Experimental exploration, with detector systems that have no specific biases built in, is strongly encouraged and will most certainly result in new results and concepts just as advances in experimental methods have always been met by equally important advances in theoretical studies.

Symmetries using simple formulations, for example the interacting boson model (IBM) using s- and d-bosons with its variants and extensions, have allowed results with a high predictive power and suggesting new experiments to be presented. This framework has led, for example, to the suggestion and subsequent discovery of scissor-like motion in strongly deformed nuclei. More recently, such excitations have been suggested for nuclei with a large neutron excess. Symmetry dictated truncations have also allowed for an algebraic formulation to treat shape coexistence and the appearance of various shapes in a single nucleus. Examples for the very neutron-deficient Pt, Au, Hg, Tl, Pb, Bi and Po nuclei amply illustrate this issue.

Dynamical symmetries may well be associated with the way the mean field will start changing when approaching dilute neutron-matter conditions or, in the opposite direction, when a large set of extra protons is present. This field where the microscopic features of the nuclear many-body system are expressed in various symmetries, for example the way the mean-field and the single-particle spin-orbit partner splitting will evolve, is still in its infancy and needs thorough theoretical study and experimental tests.

2.4 Nuclear Astrophysics far from Beta-Stability

Explosive burning in astrophysical environments always involves unstable nuclei. This means that either experimental knowledge or accurate theoretical predictions are required. In a number of cases nuclei far from stability are also encountered. Prominent processes are explosive hydrogen burning (the rp-process) on the surface of accreting white dwarfs (novae) or neutron stars (X-ray bursts), as well as rapid neutron capture (the r-process) in very neutron-rich conditions of supernova explosions or the decompression of neutron star matter.

The rp- or r-processes, which can involve nuclei with proton or neutron separation energies as low as 1-2 MeV, often attain reaction (chemical) equilibria for proton or neutron captures at temperatures close to $10^8$ K, relating the nuclear abundances to the mass differences via chemical potentials. The most important nuclear properties are then masses (including the essentials of nuclear structure, shell effects and deformation), beta-decay half-lives and partition functions. Reaction paths follow contour lines of constant neutron or proton separation energies for such equilibrium conditions.

The rp-process in X-ray bursts experiences very small proton separation energies, leading to a reaction path at the proton dripline. Particularly for elements beyond Fe and Ge, this leads into partially unknown territory. Recent calculations indicate that nuclei up to and beyond $A=100$ can be produced, making any experimental and theoretical investigations along the $N=Z$ line highly relevant. A key question is also where even-Z "peninsulas" of proton-stable nuclei permit the process of two-proton capture (with an intermediate proton-unstable nucleus) which can circumvent waiting-point nuclei with long beta-decay half-lives.

The r-process experiences neutron separation energies of the order of 2-4 MeV and possibly for the formation of actinides close to 1 MeV. Experiments for nuclei with such separation energies only exist along the $N=50$ and $N=82$ magic neutron numbers close to the $A=80$ and $A=130$ r-process peaks. As mentioned earlier, one of the major topical issues in nuclear physics focuses on the question of whether shell closures remain strong far from stability or whether they fade and vanish at the driplines. A weakening of shell closures far from stability would have
a direct impact on r-process calculations. It is therefore of paramount importance to investigate such effects by continuing experiments to smaller Z values along N=50 and N=82 and possibly approach A=194,195,196 for N=126. It is not expected that in the near future experiments will reach such neutron-rich nuclei for which very strong deviations due to shell quenching can already be encountered. The challenging role for theoretical investigations is to define possible observables which already permit such effects to be seen at their onset; still closer to stability.

As well as masses, beta decays and possibly electron captures and weak interactions with neutrinos are important. Measurements of spin response functions of nuclei are also needed in order to understand neutrino reactions in supernovae. A new and improved look at (beta-delayed) fission and fission yields is also called for, with a view to identifying any possible influence on the r-process. The location of the r-process path and the influence of fission will also determine whether superheavy elements are, or have ever been, produced in nature.

Individual reaction cross-sections are important in explosive environments where no reaction equilibria are attained, including ignition and freeze-out phases from equilibrium. This opens up the challenge of investigating any ingredient that enters into theoretical nuclear cross-section predictions, such as level densities (including nuclei far from stability) or the gamma-width, linked to giant dipole resonance properties and their possible dependence on extended neutron skins far from stability. Lower temperatures are encountered in novae where reaction equilibria are not attained and individual proton-induced reaction cross-sections on proton-rich unstable nuclei up to Si, S and possibly Ar are highly relevant. Such reactions are uncertain and presently, with a few exceptions, only explored indirectly via charge-exchange reactions. Trigger reactions during or shortly after the ignition of an X-ray burst are also essential. In the early ignition phase the break-out reactions from the hot CNO-cycle $^{15}\text{O}(\alpha,\gamma)$, $^{14}\text{O}(\alpha,p)$ and proton captures on the even-Z $^{12}\text{C}$ nuclei like $^{32}\text{Mg}$, $^{32}\text{Si}$, $^{32}\text{S}$, $^{32}\text{Ar}$ and $^{30}\text{Ca}$ have been identified as key reactions in competition with beta-decays. Future experiments with secondary radioactive ion beams will be highly relevant.

2.5 Cross-Connections with Other Scientific Fields

An important facet of nuclear science is the abundance of applications in other fields. In several of these, access to specific radioactive isotopes or sets of isotopes is essential. Radioactive nuclear beams are also needed here for further progress. In some fields new isotopes need to be produced, in others known isotopes must be made available with higher intensities or with higher purity. A closely related subject is nuclear astrophysics discussed in the previous section. This section gives some more examples of how radioactive nuclear beams have implications outside nuclear physics itself.

Nuclear physics contributes, as it has done on many occasions in the past, to our understanding of the fundamental interactions. Precision measurements of selected beta-decays help to probe details of the weak interaction. The present limits on scalar interactions, for example, come partly from $^{32}\text{Ar}$, which is one nucleus away from the dripline. Even more exacting tests will come out of experiments on $^{17}\text{F}$, $^{37}\text{K}$ and $^{38}\text{mK}$. Tests of atomic parity violation, presently done on stable Cs, can be extended with RNB to the whole chain of Cs isotopes or to the radioactive element Fr.

The atomic structure and chemical properties of the very heaviest elements is also an open frontier at present. Atomic structure has not been tested above Es (Z=99), whereas chemical properties have so far been investigated up to Sg (Z=106). The strong electric fields encountered here will give an important test of QED. To reach this goal experimentally we need to progress in the production of superheavy elements and to develop ion trap techniques for these heavy nuclei.

Nuclear solid state physics is an established field of its own. Many techniques, such as the use of radiotracer, Mößbauer spectroscopy,
emission channelling (Fig. 2.6), perturbed angular correlation spectroscopy and $\beta$-NMR, require radioactive isotopes directly. Other techniques, such as deep level transient spectroscopy, photoluminescence spectroscopy and electron paramagnetic resonance spectroscopy can benefit highly from the use of radioactive atoms since the chemical nature of the isotope changes in the radioactive decay. Common for all techniques is the need for pure beams of radioactive isotopes at high intensity. Much research has so far been done at beam energies below 100 keV. The availability of RNB facilities with increased intensity and with beam energies in the range 300 keV – 10 MeV would open up many new possibilities in this field. Several nuclear medicine or biophysics programmes employing RNB have also been performed. These fields are in a state of very rapid development and could become an important application in the future. The RNB demands would be similar to the ones of nuclear solid state physics.

One should also not forget “intellectual cross-connections”, the cases where concepts developed within one scientific field turn out to be applicable elsewhere. The nucleus is an archetype of a mesoscopic system, it contains not very few but also not very many particles, and both bulk and surface properties are therefore important. Concepts developed within nuclear physics have already been exported to other fields, such as atomic clusters and nanophysics. A similar interaction across different fields of physics is taking place for few-body systems at present. Here in particular atomic and molecular physics and (light) nuclei close to the driplines are involved.

2.6 Burning Issues

In conclusion, RNB physics has been driven by remarkable discoveries that have added new elements to the nuclear paradigm. Having only explored a part of the nuclear landscape, we can expect that new discoveries will be made in the light of the new developments in accelerators, detectors and data analysis. Over the last decade a theoretical framework of growing predictive power has been emerging. This will undoubtedly help us to answer a number of new questions.

Experiments with RNB will undoubtedly provide new possibilities for research with very good chances of finding unexpected phenomena. High priority should thus be given to systematic investigations of nuclei spanning the whole interval from stability towards the edges of instability. At the same time, serious attempts must be made to take one further step in carrying out calculations on as fundamental a level as possible.

There are, at present, a number of identified challenges and exciting issues that will be addressed in the coming years. However, it may be expected that in the near future, through the new experimental programmes, unexpected observations may modify and deepen our understanding of the nuclear many-body system.

- Position of the driplines. We are approaching a delineation of the proton dripline, but are — except for the lightest nuclei — still far from reaching the neutron dripline. Experimental as well as theoretical
progress is needed before we can obtain a satisfactory understanding of the borders of the nuclear chart and learn whether or not there are stable or long-lived structures beyond the driplines. As for both light Borromean systems and SHEs, the border is not likely to be sharp. Understanding the behaviour of very neutron-rich nuclei could help in elucidating neutron matter properties that are needed for calculations of neutron stars.

- **Beyond Z=112.** This is the present upper limit of the periodic system, the superheavy nuclei. Experimental indications for nuclei in this region were reported recently. Further data on superheavy nuclei with more protons or with more neutrons than the ones already established should allow us to elucidate nuclear structure in this upper end of the periodic table.

- **Far from stability.** The exploration of series of isotopes and isotones, progressively moving away from the region of stability, has brought many surprises (new shapes at low energy, phase coexistence and intruder states to name but a few). Learning about the evolution of these series in moving even further out may give access to a full understanding of these phenomena. Moreover, experiments may bring out the missing elements in order to reach a unified understanding of these phenomena or indicate hints of new symmetries governing the nuclear many-body system.

- **N=Z up to $^{100}$Sn.** The N=Z line is where the Wigner term arises, its origin has still to be clarified. It is also where np-pairing may show up. What is greatly needed is a study, using the best interactions, of how the $T=0$ and $T=1$ fields are built up and how their interplay might influence nuclear structure properties. Theory predicts that pairing correlations weaken with increasing temperature and rotational frequency, so that, for example, odd-odd N=Z nuclei will have a transition from $T=1$ to $T=0$ pairing with increasing rotation. The detailed and systematic mapping of this transition is an important indication on how nucleons organize themselves in the nucleus.

- **Heavier halos.** A genuine halo depends on predominance of only two halo particle motions, $s$ and/or $p$. The lesson being learned in ongoing quantitative studies of light halos (in He, Li and Be) must be tested in heavier halos. As a step towards heavier systems, evidence for halos in heavy B, C and O isotopes has to be clarified. The issue of low density multineutron systems, both in light and heavier nuclei, is of great general interest, addressing the question of when and what kind of cluster structures emerge in weakly bound systems.

- **The continuum structure** of nuclei close to the driplines, in particular for neutron-rich nuclei, is important for a full understanding of these nuclei. One example among light nuclei is the halo phenomenon where the role of binary subsystem resonances should be clarified. Unbound nuclei are beginning to be explored and could provide information that is essential for a systematic understanding.

- **Structural changes at the driplines - changes in shell structure.** There is experimental evidence at N=8, N=20 and N=28, as well as indications from analyses of the r-process, that the shell structure changes as one moves towards more and more neutron-rich nuclei. There are suggestions that this could be a general phenomenon. A detailed understanding of the precise way in which the proton-neutron interaction influences the mean-field and the subsequent single-particle ordering is urgently needed.

- **The r-process path, the rp-process.** One of the recent breakthroughs in experimental nuclear astrophysics has been the half-life measurement of a few nuclei on the r-process path with N=82. An experimental continuation of this work and a theoretical effort to better predict the structure in these important nuclei has high priority. For the
rp-process taking place in very proton-rich nuclei one cannot apply the statistical model and more experimental data are needed in order to understand the complete reaction network. A physics understanding of proton emitters is important.

- **Nuclei with large isospin.** Nuclei with a more extreme $N$ to $Z$ ratio than those of astrophysical relevance also present important challenges. On the proton-rich side ground-state proton radioactivity has recently provided a substantial increase of structure information. On the opposite side the very neutron-rich systems are where major changes in nuclear structure could take place, for example, neutron excesses so large that the neutron and proton degrees of freedom partly decouple.

- **Fusion reactions involving neutron-rich beams.** There has been speculation that nuclei with a large neutron surplus might give larger cross-sections for fusion or neutron transfer reactions. In general, the dynamic consequences of having excess neutrons (and perhaps even neutron skins) need to be explored.

- **Pairing correlations.** In both $T = 1$ and $T = 0$ channels pairing correlations have to be better understood. Tools that will help to achieve this end are various transfer reactions.

- **Reactions.** Encompassing reaction theory to the characteristics of weakly bound systems is essential for extracting reliable structure information, and is also of general reaction-theoretical interest, given these unique systems.
3. Present World-Wide Situation of Radioactive Nuclear Beam Facilities

3.1 Introduction

The basic methods used to produce Radioactive Nuclear Beams (RNB) are depicted in Fig. 3.1.

In an ISOL-type facility, radioactive nuclei are produced essentially at rest in a thick target, a catcher or a gas cell bombarded with particles from a primary source or driver accelerator. After ionization and selection of a specific mass by electromagnetic devices, these nuclei are accelerated in a post-accelerator. For the in-flight method, an energetic heavy ion beam is fragmented or fissioned while passing through a thin target and the reaction products are subsequently transported to a secondary target after mass, charge and momentum selection in a fragment separator. Since the reaction products are generated in flight, no post-acceleration is required. There are, however, advanced ideas for creating a hybrid version where the fragment beam first is stopped in a gas cell, separated and then post-accelerated.

The ISOL method produces high intensity and high quality RNBs generally at energies up to 25 MeV/u. The lifetimes of the accelerated radioisotopes are limited downwards by their extraction time from the target and their transfer time to the ion source, as outlined in Chapter 4. In-flight facilities are optimum for higher energy (above about 50 MeV/u) beams of very short-lived (down to hundreds of ns) nuclei. These beams can be collected and cooled to high phase space density beams in storage rings using various cooling methods. The resulting beams from the ISOL and in-flight RNB facilities are highly complementary, and both types of facility are necessary for pursuing the scientific goals of the nuclear physics community, as will be substantiated in various chapters of this report.

3.2 ISOL RNB Facilities in Europe

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

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

The SPIRAL facility at GANIL, Caen, France, belongs to the same category. The driver accelerators are the GANIL cyclotrons delivering heavy ion beams at energies up to 95 MeV/u with a maximum beam power on the target of 6 kW. The post-accelerator is a new cyclotron CIME, which also acts as an isobaric mass selector and which delivers RNBs between 2 and 25 MeV/u. All components of SPIRAL have been commissioned, and the facility should be operational during autumn 2000.

Combination of a driver proton synchrotron and a linac as post-accelerator
The front runner in this category is CERN’s ISOLDE in Geneva, Switzerland, which has been delivering a broad spectrum of isotopes with 60 keV beam energy for more than 30 years. These have been used in a wide variety of experiments ranging from nuclear physics through nuclear astrophysics to solid state physics. The driver accelerator is the PS booster, which delivers a 1.4 GeV proton beam with an average intensity up to 2 µA, the maximum beam power deposited in the production target being about 2 kW. ISOLDE will be extended to energies up to 2.2 MeV/u by post-accelerating the ISOLDE beams with a linac. The new facility, called REX-ISOLDE, will be operational in 2000.

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

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

Combination of a reactor as driver and a linac as post-accelerator
There exist several front runners in the production of low-energy fission fragment beams, the OSIRIS facility at Studsvik, Sweden being one example. Post-acceleration of fission products was first planned at the high flux reactor of the ILL, Grenoble, France, in a project called PIAFE. This concept was later transferred to the high flux reactor under construction at Munich, Germany, where, under improved conditions, the new fission product accelerator MAFF is be-
ing built. The post-accelerator will be a linac, producing intense neutron-rich RNBs up to 7 MeV/u. Besides thermal neutrons from a reactor, fast neutrons from the break-up of deuterons may also be used for the production of radioactive nuclei in a $^{238}$U target. This scheme is presently explored within the European RTD programme SPIRAL Phase II.

### 3.3 ISOL RNB Facilities Outside Europe

In North America, ISOL RNB facilities exist at TRIUMF, Vancouver, Canada, ORNL, Oak Ridge, USA and ANL, Argonne, USA. The ISAC project at TRIUMF uses a 500 MeV, 100 μA proton synchrotron as driver accelerator, depositing a 50 kW beam power in the target, and a linac up to 1.5 MeV/u as post-accelerator, a second stage up to 6.5 MeV/u is under consideration. ISAC is thus similar to REX-ISOLDE and the SIRIUS project in Europe. It has successfully sent a 500 MeV 10 μA proton beam to the target-source assembly, and tests at 100 μA are scheduled in 2000. At ORNL, the Holifield Radioactive Ion Beam Facility (HRIBF) is similar to EXCYT in Europe. The driver accelerator is a cyclotron, producing proton, deuteron and alpha-particle beams at energies between 50 and 100 MeV with currents of 10 to 20 μA. The post-accelerator is a 25-MV tandem. At ANL, exploratory RNB experiments have been carried out using $^{18}$F and $^{56}$Ni radioactive nuclei produced off-line and post-accelerated by the ATLAS facility to energies between 6 and 15 MeV/u. A project also exists at the LBNL, Berkeley, USA, called BEARS, which plans to use, as driver accelerator, a medical cyclotron producing 10 MeV, 40 μA proton beams, and as post-accelerator, the 88° cyclotron. It would be similar to the Louvain-la-Neuve RNB facility in Europe.

A major project for a next generation ISOL RNB facility has recently been elaborated in the USA. Called Rare Isotope Accelerator (RIA), it will use a linac as driver, producing heavy ion beams up to uranium at energies up to 400 MeV/u and with intensities up to 1 pμA. These beams will be fragmented or fissioned in a high power semi-thick target and the fragments, after selection in a Fragment Separator, will be stopped in a gas catcher/ion guide chamber. The resulting low energy $^1$ radioactive beams will be post-accelerated by a linac to energies up to 15 MeV/u. This scheme will allow RNBs of short lifetime isotopes to be produced, and be fairly independent of the chemical properties of the accelerated elements.

In Japan, the proposed E-arena project within the Japan Hadron Facility (JHF) would use a 3 GeV, 333 μA proton synchrotron as driver, and a linac up to 9 MeV/u as post-accelerator. It would thus be similar to REX-ISOLDE and the SIRIUS project in Europe.

### 3.4 In-Flight RNB Facilities in Europe

In Western Europe, two in-flight RNB facilities are operational, at GANIL and GSI, Darmstadt, Germany. The GANIL cyclotrons produce heavy-ion beams up to 95 MeV/u, with a present maximum beam power of 2 kW and plans to increase this to 6 kW. The beams are fragmented in a high-power thin target preceeded and followed by superconducting magnetic lenses, the so-called SISSI device, which increases the useful secondary beam intensities by at least one order of magnitude. The fragments are collected and identified in the LISE device, whose performances have been considerably improved with time. At the GSI, heavy ion beams up to uranium are accelerated at energies up to 1 GeV/u by the UNILAC linac and the SIS synchrotron. These beams are fragmented or fissioned in a thin target and the fragments are collected and identified in the Fragment Recoil Separator FRS. They can be either studied in the focal plane of the FRS or cooled in the ESR storage and cooler ring, where very precise measurements of the RNB masses and lifetimes can be performed. More details on these in-flight facilities, and on recent results obtained with them, are given in Chapter 6.

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

3.5 In-flight RNB Facilities Outside Europe

In North America, the NSCL at East Lansing, USA, operates the K1200 superconducting cyclotron, which produces heavy ion beams in the 100 to 200 MeV/u energy range. These are fragmented, and the resulting RNBs are studied in the A1200 Projectile Fragment Separator. This facility is presently being upgraded. Heavy ion beams will be produced by coupling the K500 and K1200 superconducting cyclotrons; this should yield up to 1 pμA light, N = Z, ions at 200 MeV/u, and up to \(10^9\) pps heavy (such as \(^{238}\text{U}\)) ion beams at 100 MeV/u. The fragment separator will also be improved, leading to expected increases of the RNB intensities by two to three orders of magnitude with respect to the previous scheme. The project is scheduled for completion in 2000.

In Japan, the RIKEN laboratory at Saitama includes a heavy ion ring cyclotron, RRC, producing beams at energies up to 135 MeV/u, and a fragment separator RIPS. This facility is also being upgraded. The energies of the primary beams will be raised up to 400 MeV/u for light nuclei and 150 MeV/u for heavy nuclei, with intensities up to 1 pμA. Three fragment separators will be built, as well as several storage and cooler rings and an electron linac to allow the study of electron-RNB collisions. The expected completion date is beyond 2002.

In China, the IMP laboratory at Lanzhou operates a \(K = 450\) separated-sector heavy ion cyclotron, producing beams at energies up to 80 MeV/u, and a fragment separator RIBLL. Storage and cooler rings for the produced RNBs are under consideration.
4. ISOL Facilities

4.1 Drivers

The first generation of on-line mass separators and RNB facilities are using existing driver machines originally constructed for other purposes. The currently used ones range from synchrotrons and cyclotrons through linacs to nuclear reactors. Whereas the energy and intensity requirements for an RNB factory can be met by variants of all these types of machines the range of nuclei of interest varies. The time structure of the beam is another important choice to be made since it has a strong influence on the functioning and lifetime of the target.

Existing heavy-ion (HI) accelerator techniques and reactors have continuous-wave (CW) beam time-structures that are close to the optimum for an RNB facility from the point of view of maximum usable beam intensity and target lifetime.

For the choice of proton driver beams the question of whether a low repetition-rate synchrotron beam or a faster cycling linac or cyclotron beam is most advantageous has to be carefully evaluated. In the first case, the deleterious effects on target lifetime caused by the shock wave induced by the intense short proton pulse and the associated instability in accelerating voltage [2] are offset by the advantage of allowing a low-frequency bunched release combined with a delay-time enhancement as observed by ISOLDE [3, 4]. On the other hand, lifetime or maximum proton-beam intensity may be increased if the more continuous (CW) beams, which may not display these effects on the target, are chosen.

Nuclear reactors can be used as drivers employing the very large thermal fission cross-sections of \(^{235}\text{U}\). The necessary high flux reactors are readily available. A further advantage of this scheme is the strong dependence of the neutron capture cross-section on different isotopes. Thus the problems of transmutation and activation of the production target can be strongly reduced by using the appropriate structural materials. A disadvantage is that high flux reactors are multi-user facilities where the operation of the RNB facility should not interfere with other experiments. However, similar situations will possibly occur for other advanced drivers.

The ideal driver particle strongly depends on the region of nuclei needed for the physics programme. A multi-particle accelerator is therefore the most universal driver.

4.2 Nuclear Production Reactions

The production of radioactive ion beams by the ISOL method has employed a variety of bombarding particles ranging from thermal neutrons to high-energy heavy ions, as illustrated schematically in Fig. 4.1. From the wealth of knowledge gained over the last 30 years, many of the aspects of the technique are well understood. Each of the different variations has its particular advantage, such as production cross-sections, currently available intensities and range of radioactive species. In addition, for a particular driver particle, practical constraints limit the choice of techniques which determine the efficiencies of the various processes influencing the yield. The yield of a particular radioactive beam species at a point beyond the first analysing magnet may be expressed as:

\[
I = \sigma \cdot \Phi \cdot N \cdot \varepsilon_1 \cdot \varepsilon_2 \cdot \varepsilon_3 ,
\]  

(4.1)

where \(\sigma\) is the cross-section for the nuclear reactions of interest, \(\Phi\) the primary-particle current, \(N\) the effective target thickness, \(\varepsilon_1\) the release and transfer efficiency; \(\varepsilon_2\) the ionization efficiency and \(\varepsilon_3\) the mass separation and acceleration efficiency. A comparison of the relative merits of the different driver beams is given in a...
previous NuPECC report [5]. There, projected beam intensities were given on the basis of measured es at ISOLDE and other ISOL facilities, which the working group agreed at that time could be achieved in an intensive development programme. Meanwhile such programmes have started in several laboratories worldwide. The essential features and the recent developments for various driver beams are given below along with subjects for further development.

![Diagram](image)

Figure 4.1: Schematic layouts of various ISOL postaccelerator concepts.

4.2.1 Charged particles

**Low-energy protons**

Protons produced from cyclotrons at Louvain-la-Neuve and at Berkeley (proton energy $E_p = 30$ MeV), HRIIBF Oak Ridge (ORIC, $E_p < 60$ MeV) and INS ($E_p = 45$ MeV) are used as driver accelerators with beam intensities up to $500 \, \mu\text{A}$. The low energy regime opens only a few reaction channels, such as $(p, n)$ and $(p, 2n)$ reactions, which give high yields near stability. The typical cross-sections of $10–100 \, \text{mb} \allowbreak \text{allow maximum production rates in the target of } \approx 10^{14} \, \text{atoms/s.}$ The yields of nuclei far from stability are small and the range of elements that can be produced is limited because of the need for refractory target materials. Because of this selectivity, production of unwanted species can be kept low so that radioactive handling problems are largely absent. When using uranium targets, beams of fission fragments are produced at the expense of more elaborate radioactivity handling.

**High-energy protons**

Particularly high beam intensities have been obtained when the on-line mass separator is combined with an intense proton beam of 500 MeV–27 GeV energy. Owing to the thick targets (1–1500 g/cm$^2$) that may be used, primary-beam conversion ratios R into secondary radioactive beams of up to $5 \cdot 10^{-2}$ are achieved. A maximum of $3 \cdot 10^{11}$ atoms/s is produced per $\mu\text{A}$ of beam in a target of one interaction length. The three high-energy proton reactions (spallation, fission and target fragmentation) allow all nuclei to be produced with $Z < 92$. The independent formation cross-sections for these reactions can be calculated by the formulae of Rudstam [6], Silberberg and Tsao [7] and the Monte Carlo codes such as FLUKA and LAHET [8]. Since these calculations have relatively large uncertainties, experimentally determined cross-sections [9] have recently been added to the existing ones found in the compilation of Silberberg and Tsao [10] and used for a critical comparison of the various models [11]. Experimental interest in this field has recently been revived because of the need for more precise data for various new applications such as spallation neutron sources, hybrid reactors and muon sources.

The relatively low power density in the target together with the broad range of nuclear reactions has allowed a large choice of target materials and has put very few restrictions on the target and ion-source techniques that may be adopted. It should also be noted that the price for this versatility is the handling of large amounts of radioactivity. At present two RNB facilities that use high energy protons are under construction: REX-ISOLDE (1–1.4 GeV; 4 $\mu\text{A}$) and ISAC-TRIFMF (500 MeV; 10 $\mu\text{A}$).
The availability of very high proton beam intensities at existing or proposed spallation neutron sources, meson factories, neutrino-muon factories and colliders, and proposed hybrid reactors could make them very attractive locations for radioactive beam facilities since beam currents of < 100 μA could be available at little extra cost. In preparation for such a facility, at SIRIUS [12] on the ISIS pulsed spallation neutron source [13, 14], a set-up [15] has been constructed for testing an ISOLDE type target [16] in an 800 MeV, 100 μA proton beam.

Finally, we note that for the production of nuclei in certain mass regions an increase of energy of the primary beam might be preferred over increasing the beam power. As seen from the excitation curves in Fig. 4.2 for deep spallation or fragmentation reactions, a factor of two energy increase around 1 GeV gives a factor of five increase in production rate. The saturation cross-section for more exotic species may well first be reached beyond 5 GeV as seen in recent tests with 1.4 GeV protons at ISOLDE.

Light and heavy ions

Following the recent development of ECR ion-sources and accelerators the intensities of HI beams with energies of 30–1000 MeV/u have been greatly increased so that they may offer an interesting alternative to high-energy protons. In particular the somewhat longer range light ions $^3$He and $^{12}$C show a cross-section advantage for deep spallation and target fragmentation reactions [17, 18], as seen in Fig. 4.3.

![Figure 4.3](image)

Figure 4.3: Ratios of sodium beam yields obtained by fragmentation of uranium by means of 86 MeV/u $^3$He and $^{12}$C over fragmentation of uranium by means of 600 MeV protons.

Here it is seen that the ISOLDE beam-intensity ratio of sodium beams formed in 600 MeV proton and 890 MeV $^3$He, and 936 MeV $^{12}$C fragmentation of uranium increases by a factor of 10 near stability, reaching a factor of 50 on the far neutron-rich side. Using protons a similar increase may be obtained by raising the energy to 1–2 GeV. The higher excitation energy that the slow heavy particle can deposit in the target nuclei as compared to protons gives a cross-section increase for the reactions shown in Fig. 4.4 of 1–10 times that of the 3 GeV proton curve. The highest values are expected from the short-range heaviest ions. As the heavy ion mass rises, the useful target thickness rapidly drops to 4 g/cm$^2$ compared to 1500 g/cm$^2$ for 1 GeV protons. For these it becomes attractive either to further increase the energy or to make use of projectile fragmentation. The fragments can be stopped in a thick refractory target or in a gas catcher. The solid can be chosen such that the properties are optimized for the released particle whereas stopping in a gas has the advantages of preserving the ionic charge and negligible delays. The typical cross-sections for this reaction are com-

![Figure 4.2](image)

Figure 4.2: Experimentally measured excitation function for the fragmentation of gold leading to some typically light products.
parable to those for high energy proton fragmentation of heavy targets as seen in Fig. 4.5.

![Graph showing cross-sections for reactions of protons with various energies on Pb and Bi targets.](image)

**Figure 4.4:** Mass yield curve for reactions of protons with various energies on Pb and Bi targets.

![Graph showing cross-sections for production of Na isotopes with various fragmentation reactions.](image)

**Figure 4.5:** Cross-sections for production of Na isotopes with various fragmentation reactions.

### 4.2.2 High-energy neutrons

A concept for obtaining high neutron fluxes without using a critical assembly and its hostile environment has been proposed by the Argonne group [19]. Their idea, schematically shown in Fig. 4.6, is to generate an intense 100 MeV neutron beam by stripping a 200 MeV, 0.5 mA (100 kW) deuteron beam in a well-cooled low-Z target and to let it impinge on a 25 cm long (natural or even depleted) uranium target.

![Diagram of the Argonne neutron converter target concept.](image)

**Figure 4.6:** The Argonne neutron converter target concept.

The power dissipated by the neutrons in the target is relatively small compared to other particles and hence very large fluxes of neutrons can be used without overheating the target. Extremely high reaction rates can be reached because the target, at least in principle, may also be very thick.

In the Argonne case a total power of 20 kW is developed in the target, essentially due to the energy released from the fission fragments, for a luminosity \( L = \Phi \cdot N \) in Eq. (4.1) of \( L = 5 \cdot 10^{14} \text{ barn}^{-1} \text{s}^{-1} \). This, of course, relies on assumptions about the angular and energy distributions of the neutrons from deuteron break-up and the geometrical layout of the uranium target, but the order of magnitude is certainly reasonable. Experimental programmes to investigate these parameters in detail are presently under way by a European Network [20]. With a combination of experiments and simulations of the maximum power density which can be deposited in uranium targets, we may soon be able to give realistic numbers for the ultimate luminosities possible through this method. If we take the Argonne numbers, the in-target production rate for a species with a cross-section of 2 \( \mu b \), already far from stability, is \( 10^9 \) pps.

The fission and spallation cross-sections for these fast neutron induced reactions have not yet been precisely investigated. Calculations and recent tests of this concept at the
SATURNE National Laboratory [21] indicate that production rates obtained with a high-temperature, ISOLDE type UC$_x$ are comparable with those that can be obtained from a 1 g $^{235}$U target in a thermal neutron flux of $10^{14}$ cm$^{-2}$ s$^{-1}$, as indicated by the LAHET calculations [22]. Within a European Network [20], experiments to measure isotopic cross-sections and modelling studies with improved LAHET [8] codes are presently under way. Further recent progress in the modelling of the cross-sections by semi-empirical descriptions of the fission process is reported in [23, 24].

The issue of measuring the efficiencies $\varepsilon_1$, $\varepsilon_2$, $\varepsilon_3$ of Eq. (4.1) for various short-lived fission fragments obtained by irradiating thick uranium targets with neutrons in the energy range 10–100 MeV is presently being investigated by the PARRNE set-ups developed by IPN Orsay [25, 20]. The first experiments used 20 g UC$_x$ targets and also molten U targets. Substantially thicker targets are under development.

An alternative to the generation of neutrons by the break-up of deuterons is to use protons on a heavy target to produce spallation neutrons. A typical pulsed spallation neutron source, such as the proposed European Spallation Source [26], generates neutrons from a heavy target bombarded by 3.8 mA of protons at 1.3 GeV. An alternative is to use a lower current at a higher energy, for example, the 27 GeV protons from the CERN PS. Even more neutron yield may be gained by bombarding a uranium target to obtain fission neutrons in addition to spallation neutrons.

4.2.3 Reactor neutrons

The highest formation cross-sections (586 b) are found in the thermal fission of $^{235}$U as shown in the example of Fig. 4.7. The high production rates of neutron-rich nuclei that may be obtained in the fission-product mass region of 80 $< A <$ 140 have for many years been exploited by several on-line mass separators [27]. By locating their target next to the core of the reactor the Studsvik group is currently using the highest neutron fluxes of $10^{14}$ cm$^{-2}$ s$^{-1}$ [28]. Due to the restrictions in terms of space, access and other technical reasons they have not been able to use the most efficient ion-source techniques: they work with a long-lived but dual-mode ion-source which has, depending on the element, an efficiency a factor of 3 to 100 lower than today’s standard. At the high flux reactor of the ILL in Grenoble the project PI-AFFE for a fission fragment accelerator with $10^{14}$ fissions/s was developed [29, 30]. It was abandoned after better technical conditions became available at the new Munich high flux reactor FRM-II. At FRM-II, a local neutron flux of $1.5 \times 10^{14}$ cm$^{-2}$ s$^{-1}$ will be available. The Munich Accelerator for Fission Fragments (MAFF) [31, 32] is currently being built. For the approved configuration $10^{14}$ fissions/s are obtained from thermal induced fission of 1 g $^{235}$U. Different ion sources are under development. After some experience with the system a further increase by a factor of 10 in U-content and output seems feasible.

![Figure 4.7: Cross-sections for production of rubidium isotopes by various nuclear reactions.](image)

4.2.4 High-energy photons

Fission in thick uranium targets may also be efficiently induced by high-energy photons, which generate similar low power in the target as the neutrons.
In a project proposal originated at Chalk River Laboratories, the use of a high-power electron linac as the driver accelerator for a Radioactive Ion Beam facility is proposed. An electron beam of 30 MeV and 100 kW can produce nearly $5 \times 10^{13}$ fissions/s from an optimized $^{235}$U target and about 60% of this from a natural uranium target [33].

The Flérov laboratory in Dubna proposes to use their 25 MeV, 20 μA electron microtron MIT-25 to produce bremsstrahlung photons in order to induce fission reactions in a 100 g uranium target [34]. With this scheme, having 0.5 kW, they claim a fission yield of about $10^{11}$ fissions/s for a total cross-section of about 0.5 barn.

4.2.5 Conclusion

In concluding this section, however, it should be noted that the cross-sections alone are insufficient to decide on the best suited reaction for production of RNB, since the other factors of Eq. 4.1 may change the picture given in this section dramatically.

4.3 Targets and Ion Sources

4.3.1 The target and ion-source unit and its characteristic parameters

The radioactive nuclei formed in a thick target or catcher are brought to rest and then have to be separated from the bulk and converted into an ion beam. This operation can be broken down into three distinct processes: ($\varepsilon_1$) high temperature thermal diffusion to and release from the target surface and transfer by diffusion through the transfer line from the target to the ion source, ($\varepsilon_2$) ionization and ($\varepsilon_3$) the mass separation. It was quickly realized that the efficiencies of these processes often play a more important role in determining the resulting secondary-beam intensities than the factors $\sigma \Phi N$, which determine only the production rate in the target. In fact the efficiencies that can be obtained for a given product element strongly depend on the properties of the refractory target materials, pressure and purity of the catcher gas, the primary beam and its time structure, and the type of ion sources which could be adapted to the particular environment. The basic parameters that determine the efficiencies of these new radiochemical separation methods, which for a given product element take place in the target-catcher and ion-source unit, are the temperature, diffusion constant, desorption enthalpy, range, neutralization rates, molecular-ion formation rates, gas-flow patterns and ionization potential [35]. For the choice of target material and construction materials it is essential to know these parameters, which to some extent can be found in the literature. It is not possible to calculate the parameters $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_3$ with sufficient precision for a given nuclide due to the uncertainty and spread in the temperature distribution, grain size distribution and purity. The efficiencies $\varepsilon_1$ and $\varepsilon_2$ have to be determined off-line or on-line using various methods with good precision. The determination of $\varepsilon_1$, which is a function of half-life, can only be done by an on-line determination of the delay function, that is the probability that an atom formed at time 0 is extracted from the ion source at time $T$ [36]. For this the most powerful method is to monitor the output of the wanted species from the prospection target and ion-source system into which they are continuously implanted as an energetic H1 beam. Depending on the element, values for $\varepsilon_1$ and $\varepsilon_2$ in the range 10–90% are not unusual and a typical half-life dependence of $\varepsilon_1$ is shown in Fig. 4.8.

![Figure 4.8: The half-life dependence of the release yield caused by the decay losses in the target and ion-source.](image)
Another important parameter is the lifetime of the target and ion-source unit. Current techniques allow operation of these units for periods from a few days up to several months before they have to be replaced. During this period, sintering, migration or chemical dissociation of the target material, in conjunction with the deleterious effects of the driver beam on the surrounding mechanical structures, eventually causes a failure. For this reason much effort has been put into finding the most economical ways to produce such consumable units. This has, with few exceptions, led to the choice of a relatively simple and inexpensive ion-source technique of which an example is shown in Fig. 4.9 [27].

![Ion Source Assembly Diagram](image)

**Figure 4.9:** A typical target and ion-source unit, where the target container is connected to an ion source via a transfer tube.

It produces singly charged, continuous ion-beams with high efficiency and emittances of typically $\varepsilon \sim 30\pi$ mm mrad. In this respect the resonant laser ion-sources now coming into general use are also particularly interesting. Obviously for the use of an ISOL as injector for a heavy-ion accelerator, the conversion of the reaction products into a higher charge state, possibly bunched beam, at present receives much attention as seen from the discussion in later chapters. Three routes are generally followed here: pre-acceleration and stripping (which also allows negative ions to be produced for acceleration in a tandem), direct coupling of an ECR ion-source to the target, and charge breeding of the mass-separated beam of singly charged ions in an EBIS or ECR secondary ion-source.

### 4.3.2 Chemically challenging elements

At the various ISOL facilities radioactive ion-beams have been produced for about 70 out of the 92 naturally occurring elements. Although much engineering effort can still be done to optimize the targets there remain 22 elements that have proven difficult to develop for chemical reasons. They belong to the transition elements found in the groups 5B to 7B and 8 of the periodic system. Due to their refractory nature they are often used as target element and construction materials in ISOL targets and ion-sources. The elements boron, sulphur, silicon and phosphorus belong to the class of elements which are refractory or form predominantly refractory compounds with the usual target and ion-source metals or impurities present in them. Methods for their efficient release from solid targets and transfer into an ion source still remain to be developed.

There is no lack of ideas on how to develop such beams in connection with thick targets irradiated by high-energy beams. By suitable selection of target and ion-source materials or by chemical-evaporation techniques it seems to be technically possible for a number of them. The very limited resources expended on Nb, Zr, Hf, Ta and W show that beams can successfully be made by addition of CF$_4$ to the target [37].

Beams of the transition elements have been made by means of the IGISOL technique [51] and other gas stopping techniques in which the recoiling fragments are thermalized and reduced to the $^{1+}$ ionized stage in high-purity He gas. Until now the beams have been of relative low intensity (up to $10^6$ ions/s) but rather insensitive to the chemical nature of the element. The technique shows good promise for further development.

Intense beams of chemically challenged elements can be developed but require a dedicated
research effort of several man-years. The successful development of the $^{13}$N and $^{15}$O beams at Louvain-la-Neuve [38] is an example of this.

### 4.3.3 Thick targets

Radioactive particles are produced in the interaction of an energetic driver beam with the target material. Thick targets absorb the secondary radioactive particles but not necessarily the primary beam, which can range from protons to heavy ions. The radioactive ions then diffuse out of the target material and effuse through the ionizer. The target must be at a high temperature to obtain significant diffusion and effusion before the particles suffer radioactive decay. Targets are generally constructed from small grains or foils in an open matrix to aid the speed of both diffusion and effusion. The performance of the ISOLDE targets has been reported for a large number of radioactive species with protons at 600 MeV [39].

Considering Eq. (4.1), the yield of radioactive ions will improve with the driver beam current, $\Phi$, and the target efficiency $\varepsilon_1$. A high power (up to 30–40 kW) tantalum target (Fig. 4.10) has been developed [16] for proton beams up to 100 $\mu$A and the GANIL graphite target (Fig. 4.11) will accept heavy ions of 6 kW beam power [40]. Proton targets of non-refractory materials, powders and liquids are considered possible [23] at 30–40 kW, if they are large enough to keep the power density down to reasonable levels.

The parameters governing the target efficiency are the diffusion coefficient for the target material, the effusion through the target void and the effusion through the ionizer. The time constants of these processes, in relation to the decay time of the radioactive particle, determine the efficiency. The diffusion coefficient is a property of the target material and the operating temperature. The diffusive delay is minimized by choosing a high diffusion coefficient and making the material as thin as possible. The effusion terms are governed by geometry (a high conductance is required) and the particle dwell time (sticking) on the surfaces. A high temperature reduces dwell times. Some particles chemically interact with the target materials to form stable, low vapour pressure compounds, resulting in very low yields. It has been shown [41, 42], however, that by flowing a chemically reactive gas through the target it is possible to form a volatile molecule.

![Figure 4.10: The RIST target and ion-source assembly for top loading into the target shielding.](image)

![Figure 4.11: The Spiral ECR high power graphite target.](image)
The target efficiency is currently being investigated by a RAL/ISOLDE collaboration and by GANIL. Considerable improvements in knowledge of the diffusion and effusion characteristics are being made by theoretical modelling studies [43, 44]. In particular, the efficiency of a tantalum target for $^{11}$Li production has recently been improved by a factor of 40 over that of the standard ISOLDE roll foil (25 μm thick) target. Very thin foils of 2 μm thickness were used in an open geometry that improves effusion as well as diffusion characteristics [45]. Reductions in diffusion delays are also being made at GANIL by using fine graphite powders of 2 μm diameter in an open matrix [46].

It is believed that there is considerable scope for engineering the targets to optimize their performance efficiency for particular species by altering the geometry. However, it will be difficult to reduce the delay times to below a few tens of ms even for the most volatile species. Designs to overcome surface sticking of non-volatile species by incorporating a discharge within the target to sputter the surfaces have been suggested [47]. Flowing a gas through the target to form a more volatile molecule could also be done. The use of new materials that have an open honeycomb structure and thin walls may be useful in reducing the delays due to diffusion and effusion. Effusion could be improved by the incorporation of ionization and suitable electric fields within the target [23, 48].

The systematic design and engineering of thick targets has only just commenced and it is believed that their development has the potential for significant improvements in yields and range of species.

4.3.4 Thermalization of products in a gas cell

The thermalization principle of reaction products in a gas cell has been used successfully for many years to produce low-energy ion beams of short-lived radioactive nuclei at on-line isotope separators. This has resulted in beams of short-lived isotopes that, because of their chemical properties, are difficult or impossible to produce using high-temperature target-ion source systems [49]. In this so-called IGISOL technique [50, 51] reaction products from light- and heavy-ion induced reactions (fission as well as fusion evaporation) are stopped in a high-pressure helium gas (between 100 and 500 mbar). Some of the reaction products survive in a $^{1+}$ ionic state due to the high-ionization potential of helium and the presence of very dilute impurities. The ions are swept out of the gas cell by the gas flow and are accelerated and mass separated. The major advantage of this technique is its shortened delay-time, of the order of milliseconds, essentially determined by the evacuation time of the gas cell. For larger cells the delay time can even be shortened by using guiding static or RF electrical fields [52]. Measured efficiencies, defined as the ratio of the mass separated beam intensity to the number of reaction products that recoil out of the target, vary according to the nuclear reaction used. For light-ion induced fusion reactions, efficiencies between 1 and 10%, for heavier projectiles efficiencies up to 1% and for fission reactions efficiencies up to 0.01% have been reported [51]. It should be stressed that the latter two were only possible by avoiding the primary beam going through the gas cell. This beam creates a weakly ionized plasma that deteriorates the efficiency substantially. This so-called “plasma effect” needs further careful investigation. For example, in the specific role of gas impurities, the plasma created by the secondary beam and by the radioactivity should be clarified. In the absence of a plasma, higher efficiencies up to 40% have been obtained using recoil ions from an alpha source that was placed inside the helium filled gas cell [53] while about 87% of americium ions produced in a $(d, 2n)$ fusion reaction survived thermalization in an argon buffer gas [54]. Another advantage of the ion-guide technique is the fact that its performance is less dependent on the chemical properties of the atoms of interest. For instance, short-lived isotopes ($T_{1/2} \sim$ ms) from refractory elements have been produced [50]. It should nevertheless be stated that chemical reactions with impurity atoms (even on the sub–ppm level) do play a role which is not fully understood and is subject to further investigation [55, 56]. This results, for example, in different efficiencies for different elements or in molecular ion contamina-
tion. Finally it should be noted that at present the ion-guide technique is limited to thin targets and thus modest production rates. An interesting development has been the implementation of resonant photo ionization in a gas cell [57, 58]. This has allowed the use of high-pressure argon gas (typically 500 mbar) as a buffer gas and thus increased the stopping efficiency. The laser ion source of which a schematic drawing is shown in Fig. 4.11, makes use of the atoms that have been neutralized after thermalization. Efficiencies of 6% have been obtained for light-ion induced reactions while between 0.1 to 0.5% efficiency was reached for light-ion induced fission reactions [57]. Due to resonant ionization, the laser ion source is element selective. A selectivity, defined as the ratio of the production yield with the laser tuned on-resonance to the production yield obtained when the lasers were switched off, of up to 300 was obtained. Decay studies of neutron-rich Ni and Co isotopes have been performed with this source using the Z-identification capability [59]. The laser ion source also allows a whole series of ion-guide related issues to be studied in detail. These include, for example, interaction of ions with impurity gases, neutralization rates in weakly ionized plasmas and evacuation scenarios. A final development that is closely related to the gas cell is the use of a multi-pole radio frequency ion trap to transport the ions from the high-pressure zone to the high-vacuum zone prior to acceleration [60]. With this ion trap, transport efficiencies of up to 90% are obtained. Furthermore, due to buffer gas collisions, the ions are cooled during transport and, for example, mass resolving power increased from 300 when the traditional skimmer electrode was installed to 1450 with a sextupole radio frequency trap. The energy spread of the ions was also less than 1 eV [60]. More details on buffer gas cooling in ion traps will be given in further chapters.

A new and interesting concept, called RIA, for the production of intense radioactive beams of very exotic isotopes based on the ion-guide principle has been recently proposed [61, 62]. This concept, currently under study, proposes heavy-ion fragmentation (for example $^{238}$U at 200 to 400 MeV/u) as the primary production mechanism. The fragments are sent through a fragment separator and are subsequently retarded prior to injection into a large gas cell. In this way plasma creation by the primary beam is avoided. After thermalization the ions are guided to the exit-hole using electric fields. They are evacuated from the gas cell and are transported to the first acceleration stage using multi-pole radio frequency guiding fields similar to the laser ion source described above [56]. Note that a similar concept whereby a gas filled separator was coupled to an ion-guide system and where heavy-ion fusion evaporation reactions were used, has been investigated [63]. The potential advantages of the fragment separator – ion guide approach are the very short delay times (of the order of 1 ms) and the fact that its expected performances are less dependent on the chemical properties of the isotopes of interest. This would allow the gap of the isotopes of refractory elements that are not accessible using high-temperature techniques to be covered as well as certain very short-lived isotopes with half-life below the 10–100 ms range (depending on the element). Many questions such as plasma effects and interactions with gas impurities related to this concept still need to be resolved. Note that the heavy-ion fragmentation reaction can also be used with a high-temperature target. Here the “target” function and “catcher” function are separated and use is made of the fact that the reaction products (lower Z) have a larger range than the primary beam. In this way the target material can be chosen to cope with the high power deposition of the primary heavy-ion beam.

Specific problems related to the above concepts are studied in a European effort in the framework of the EU EXOTRAPS [64] project.

4.3.5 Element-selective, multistep, resonant laser ion-sources

The principle of stepwise, resonant laser ionization has in recent years been developed at GSI [65], ISOLDE [66], Gatchina [67], Leuven [68], Mainz [69], Orsay [70] and Takasaki [71]. The simplicity of the laser-ionization cavity adjacent to the target makes this ion source particularly interesting for the hostile environment near an
on-line target. In addition, its speed, efficiency and selectivity match or exceed those of most other ion sources. As shown in Fig. 4.13, up to three laser-generated light beams of different wavelengths are sent into a cavity very similar to that of a standard ISOLDE tubular surface-ionization ion-source [72]. The laser interaction with the products flowing through this cavity allows in principle an extremely high element-selective ionization. In practice suppression of any isobaric surface-ionizable element by more than two orders of magnitude has been difficult to achieve because of the high temperature needed in the cavity in order to keep the element of interest in the gas phase. Since the laser ions are currently bunched at 10 kHz, the most often used laser frequency, the selectivity can be considerably improved by shortening the laser ion pulse and gating the separator to it. On the other hand the theoretically obtainable efficiency is as high as 30%, determined by the frequency and intensity of the available laser light. The experimentally determined efficiencies are typically 10–20% and often exceed those obtained with plasma discharge ion-sources. Furthermore the absence of insulators in this source allows operation at a higher temperature, which results in shorter delays and less stable beam contamination. As mentioned above this ion-source principle also works with reaction products stopped and neutralized in gas cells [57, 58] and it generally holds much potential for further development. It is currently being developed for shorter laser ion pulses, further elements, enhancement of the bunching by means of laser ablation of condensed material [73] and reduction of the thermo-ionized current [74]. The ionization efficiency is determined by the existence of a viable excitation scheme for which the light can be produced by means of traditional dye lasers pumped by 10 kHz copper-vapour lasers. This rather elaborate method the frequency tripling in non-linear systems has now been used successfully in order to ionize efficiently atoms of elements with high-lying first excited levels like Be, Zn, Cu and Cd [75] that require ultraviolet light. Mn [76], Ag [77] and Ni [78] have recently been added to the list of elements shown in Fig. 4.14 that can be efficiently ionized by means of present laser techniques. The development does not seem to stop here, however. As a function of the availability of high repetition rate Nd:YAG lasers which can pump tuneable solid state lasers or optical parametric oscillators, the efficiency, simplicity and range of elements may be further increased [58].

4.3.6 ECR ion-sources

An obvious choice for generating high ionic charge states is to do so directly adjacent to the target by coupling to an ECR Ion-Source (ECRIS), and in this way eliminate the need for gas, foil, electron beam or plasma stripping as discussed in Section 4.6.1. In general these sources have been successfully developed for high-intensity, stable beam generation rather than for high efficiency and short delay time as required for RNB generation. In order

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**Figure 4.12:** Gas cell with resonant photo ionization.

**Figure 4.13:** The principle of the ISOLDE laser ion source.
Resonance Ionization Laser Ion Source, using Copper Vapor Lasers

![Table of Elements]

Figure 4.14: Periodic table of the chemical elements which shows those for which laser ionization techniques have been developed.

for this technique to compete with the existing singly charged ion-source technique a number of questions have to be answered. Its efficiency and delay for production of multi-charged ions must be higher than the product of those of the singly charged sources and the efficiency of the charge multiplying technique employed downstream. In addition, the cost and inconvenience of employing such an elaborate technique in the high-radiation environment of the target must be carefully evaluated. Because of rigorous plasma confinement, ionization efficiencies of 10–40% have been demonstrated for singly charged ions of light gaseous elements. For these elements such sources have been used successfully at on-line mass separators and are promising for RNB production. A typical layout is shown in Fig. 4.15, the SPIRAL ion-source. Recent developments confirm the strength of this route for multi-charged RNBs as well, but only for nitrogen and the light rare gases. Judged from the stable metal consumption of accelerator ECR sources, multi-charge ionization efficiencies of moderately volatile elements such as Ca in a given high charge state seem to be of the order of 1%. However, it remains to be shown that this efficiency is not obtained at the expense of a very high delay time in the ion-source, since the wall temperature of these sources is so low that atoms that reach the walls remain there for a very long time. At present, there is little experience in the direct production of multi-charged radioactive metal ions. It should also be noted that the present ECR ion-sources generally give transverse emittances 10 times higher than conventional 1+ ISOL sources. Current developments of cylindrically symmetric ECR sources, known as MONO, show the promise of a low cost, low emittance solution for the production of singly and multiply charged ions.

![Spiral Target and ECR Ion-source]

Figure 4.15: The SPIRAL target and ECR ion-source combination.

4.4 R&D for Targets and Ion Sources

Development of the presently available ISOL-type radioactive ion-beams has most often been physics-project driven. Independent groups
of physicists and technicians have developed beam for specific purposes, placing less emphasis on the measurements and understanding of the physics and engineering parameters governing the function of the target catcher and ion sources. A systematic programme of target and ion-source development, to make beams of all elements, on a scale matching the accelerator developments leading to the intense beams available from the driver accelerators was never undertaken.

Since the target catcher and ion source combination has been identified as the most critical element for production of radioactive beams with the ISOL method the time has come for a larger-scale development programme. This is important in order to have the necessary parameters available for the design of the next generation facilities.

From the list of subjects needing attention, given below, it is seen that specialists from a variety of disciplines are needed, a fact that clearly calls for international collaboration.

- Production cross-sections
  - Measurements of reaction cross-sections
  - Improvements and tests of calculation codes
- Targets and catchers
  - Material studies
  - Materials problems occurring at high intensity particle bombardment
  - Determination of the diffusion and desorption parameters of the reaction products
  - Chemical reaction enhanced desorption
  - Transport of Ti, Hf and Zr as halides
  - Formation and transport of C, O, S and P as CO and CO(S,Se,Te)
  - Codes for modelling the diffusion and desorption efficiency of solid targets
  - Heat transfer in high temperature targets
  - Power density and cooling
  - Liquid metal technology
  - Gas stopping
    - Capture efficiency
    - Transport properties as function of element and beam intensity
    - The role of impurities in molecular ion formation
- Laser ion-sources
  - Potential distribution across vacuum cavities
  - Laser cavity materials
  - Control or correction of the laser ion pulse shape
  - Use of new types of lasers
  - Bunching in the target by means of laser ablation
- Other ion sources
  - Construct and test sources with large slit shaped outlet areas for faster extraction
  - Construct sources of more noble materials with lower desorption enthalpies
  - Build compact ECR ion-sources with both cold and hot walls for singly charged ionization

4.5 Isobaric Mass Separation

All advanced radioactive beam facilities have a mass separator scheme in common, which is shown schematically in Fig. 4.16. The primary beam from the production target is separated in a broad range low resolution separator first to select the few masses of interest. New facilities will always operate with several beams at the same time.

In the pre-separator the main radioactivity of unwanted nuclei is deposited onto a remotely operated slit system. This is kept close to the area of the production target, it is well shielded and is retractable into a shielded container. After the pre-separator several beams are available for low energy experiments and applications. Only very few are further purified in a
high resolution separator to achieve isobaric purity. The recently developed technique of buffer gas cooling may be applied to improve the beam phase space before the second separation by several orders of magnitude. An isobaric pure beam is also injected into the high energy accelerator.

![Diagram of mass separator scheme](image)

Figure 4.16: Mass separator scheme.

The low resolution separator has a standard design, which is like the ISOLDE general purpose separator (GPS). The bending radius of the magnet should be larger than 1.5 m, the deflection angle larger than 60°. The mass dispersion is typically 0.5 m and the resolving power allows most of the isotopic contaminants to be removed. Special designs such as Mattauch-Herzog configurations [79] may be used to compensate for energy dispersion.

The slit system requires a special design from the point of view of radiation protection. It may be combined with diagnostic devices and ports for the collection of special activities onto foils. With the increased activities of future radioactive beam facilities a joint effort for optimum design is required.

It may be of interest to recombine mass separated beams into beams without mass dispersion. These beams may be cooled and transported jointly to other areas. Cooling of ions in noble gas gives the possibility of enhancing the emittance of low energy beams as a function of the length and pressure of the cooler. Figure 4.17 shows a two-dimensional cut of a gas-filled Quadrupole Ion Guide (QPIG) with the trajectory of two ions.

![Figure 4.17: Quadrupole Ion Guide.](image)

Radial ion motion is damped by the buffer gas while a longitudinal gradient caused by the segmented ion guide prevents the stopping of the ions in the structure. This potential along the QPIG can also be used to capture the ions in an electrical trap.

Buffer gas cooling of intense radioactive beams still has to be developed further, exploring the limits for maximum intensities where plasma discharge causes breakdown. It is probably advantageous to use lower gas pressures below 1 mbar leading to a longer ion guide. Furthermore heating by micromotion can be reduced for beams with a larger diameter by using a rod structure with a higher multipole than a quadrupole. After pre-separation the beam intensity has been reduced by several orders of magnitude allowing for improved beams within space charge limitations. After cooling, contaminating ions, which passed the first separator due to scattering or only partial acceleration, can be eliminated more easily.

The following three methods of isobaric mass separation are presently used for uncooled beams:

- high resolution magnets in the 1st mass separation stage;
- mass selective buffer-gas cooling in the Penning trap also used for bunching of the continuous 1+ ions;
• the use of the mass separation power of cyclotrons when they are used as post-accelerator.

### 4.5.1 High resolution electromagnetic mass separation

As discussed in [27], the properties of the three different types of analysing magnets generally used in on-line mass separators play an important role in the purity of the beams to be post-accelerated. They not only perform the isotopic separation but could, if needed, via higher resolving power, further enhance the chemical selectivity of the system by means of isobaric mass separation. In particular, the elimination of the often-abundant stable-beam contaminants (such as atomic, molecular and multi-charged beams) may be needed at this stage depending on the mass resolving power of the following post-accelerator system. Most on-line mass separator facilities to date have successfully used so-called low-current mass separators which allow beams with intensities of \( I < 100 \mu \text{A} \) to be separated with a resolving power (FWHM) of \( M/\Delta M = 2000 \). New developments show that the on-line use of high-current machines whose resolving power may be pushed towards \( R = 30000 \) is an interesting possibility. Several such systems are planned or have been built [80, 81, 82]. In addition to stabilization of all electrical and magnetic fields to high precision, these require the installation of much more elaborate beam observation equipment than is traditionally used. In particular, attention must be paid to the accelerating voltage which, due to the ionization in the air surrounding the target region, is subjected to a current load that may make it difficult to maintain the ion energy-stability required to achieve high resolution. Moreover, a systematic study of the emittance of the various ion sources has been started since it is clear that not all have minimum emittance for the same working parameters that give maximum ionization efficiency. At ISOLDE the high-resolution mass separator (HRS) with a double magnetic-analysis stage and higher order image aberration is in operation on-line [80]. In its test version at ISOLDE-3 it was, in conjunction with a surface-ionization source of slit extraction geometry, pushed to a resolving power of 11 000 at 60% transmission. This allowed separation of the \(^{37}\text{(K-Ca)} \) doublet.

Combined with a well-tuned plasma discharge ion-source, the resolution of the ISOLDE HRS is \( R = 15000 \) at 30–60% transmission when a well tuned plasma discharge ion source is used. It has been clearly realized that to bring it towards its calculated limit of \( R = 30000 \) without further losses would depend very much on ion-source developments.

Another important parameter of the magnetic analysis stage is the range of masses it permits to be brought simultaneously to the focal plane. The typical value the currently used magnets allow is only \( \pm 10\text{–}15\% \) of the central mass. This restricts the useful number of beams which the switchyard [27] may eject simultaneously to experiments. Nuclear reactions, as well as the target and ion sources, often produce a much wider range of interesting masses. A facility with a broad range magnet would permit a much more efficient exploitation of the targets, allowing widely separated masses to be ejected simultaneously.

### 4.5.2 Mass separation and buffer gas cooling of radioactive beams

The concept of using a gas filled Penning trap for accumulation, cooling and mass separation, used in commercial Fourier transform ion cyclotron resonance (FT-ICR) spectrometers in chemistry and exotic nuclear mass measurements, is now gaining importance in accelerators for RNB production [83].

In such devices, the ion beam from the mass separator is decelerated into a cooler trap, typically operated at a \( p_A > 1 \cdot 10^{-4} \text{ mbar} \). After a cooling and mass separation period of 450 ms the collected ions have undergone a loss-free mass separation of \( R = 100000 \) and are ejected with an emittance \( < 10 \pi \text{ mm mrad} \), ideally suited for injection into a charge state breeding device. The price to be paid is a maximum throughput of \( 10^8 \text{ s}^{-1} \) due to the Penning trap space-charge limit [84].
4.5.3 Cyclotron mass separation

Cyclotrons can combine the functions of mass separation as has been demonstrated at Louvain-la-Neuve [85]. For example $^{13}$N has been separated from a huge amount of stable $^{13}$C. Depending on the harmonic and the number of turns resolving powers of $R = 1.5 - 3.5 \times 10^4$ may be achieved. Although cyclotrons generally have a modest transmission and beam quality, much development effort is currently devoted to this solution.

4.6 Post-Accelerators

In order to perform experiments with fission, fragmentation or spallation products at the Coulomb barrier post-acceleration of radioactive ions either in a heavy ion linac or in a cyclotron is required. Several schemes of post-acceleration can be considered, these are sketched in Fig. 4.18. The least sophisticated method, which on the one hand is tried and tested but on the other hand is relatively expensive, is the continuous acceleration of the singly charged reaction products by a low frequency linac to stripping energies in the range of several MeV, and subsequent post-acceleration of the resulting highly charged ions in either a cyclotron or a linac [86, 19].

A more economical scheme, as yet unproven, is to use charge multiplication of the radioactive ions in an ion source, such as the Electron Beam Ion Source (EBIS) [87, 88] and the Electron Cyclotron Resonance Ion Source (ECRIS) [88, 89, 90], delivering highly charged ions for efficient acceleration in a short linac or a cyclotron [91]. This scheme requires research and development.

A synchrotron may be an alternative, particularly when cooling and breeding techniques using traps delivering pulsed beams are applied in the ion source system.

4.6.1 Charge breeding

An RTD proposal to determine the preferred specification of a technique for efficient charge transformation of exotic ions from RNB facilities by charge breeding devices has been accepted under the auspices of the Fifth EU Framework programme. This will critically influence the length and power consumption of the post-accelerator of presently built first generation facilities as well as new second generation facilities. The capability to raise the charge state from 1+ to n+, where n may correspond to a charge-to-mass ratio of 0.15 or higher, will lead to a great reduction in cost and gives the possibility of accelerating heavier masses with increased efficiency.

Figure 4.18: Schemes of post-acceleration of radioactive ions.
Current status

Several schemes of charge breeding have been considered in [91] using the two types of ion sources capable of reaching the required charge states. An overview is given in Fig. 4.19. In order to prepare the beams from the production target of an RNB facility for a pulsed linac with low duty cycle, a Penning trap can be used for accumulation, emittance cooling and bunching of the beams with an EBIS following, as will be demonstrated for the first time in the REX-ISOLDE experiment [92, 93, 94]. An additional injection scheme using the EBIS is the slow injection or “accu” mode, where the 1+ ions are continuously injected into the EBIS during the confinement period [95]. The accu-EBIS mode has the advantage that the full trapping capacity of the electron beam can be used to confine the ions while charge breeding takes place.

Another way to achieve high charge states is to use a high performance ECRIS, either directly in the production zone as discussed in Section 4.3.6 or in the stripping mode (1+/n+), as has been developed recently at ISN-Grenoble for the PIAFE project [90] and for the SPIRAL project [96, 97] at GANIL. A discussion of the use of ECRIS in RNB production is presented in [98]. The stripping mode was examined in detail by [99, 100] with the well known MINIMAFIOS source. Ion injection into the ECRIS is always continuous so that no preceding accumulation of ions is required. Ion extraction from the ECRIS can be continuous, which is the classical way, as well as pulsed using the afterglow mode [101, 102]. The ECRIS can thus be used for injection into a CW- or pulsed linac or for injection into a cyclotron.

Future improvements and investigations

For an RNB facility it is essential to have a high efficiency for the charge state breeding process in a short time compared to the half-life of the exotic nuclei of interest. Moreover, the higher intensities of RNBs from second generation facilities of up to 10^{12} ions/s must be handled by the charge breeding device. The questions of purification of the beam and bunching of the ions are important as well. Therefore the following topics must be covered in future RTD programmes.

- The number of ions that can be trapped in a Penning trap is limited due to their mutual Coulomb repulsion. Realistic simulations of the properties of the REXTRAP Penning trap system indicate that 10^4 ions could be trapped and cooled below the space charge limit into a cloud of about 0.1 mm radius and

![Figure 4.19: Schemes of charge state breeding modes with EBIS and ECRIS.](image)
a length of 5 mm [103]. This is in agreement with experimental studies at a similar trap used in a Penning trap mass spectrometer at ISOLDE. Extrapolations to denser clouds with a length of up to 30 cm, however, give a maximum number of confined ions of about \(10^9\) ions per accumulation cycle. These limits need to be explored at the REXTRAP.

- Further investigations at REX-ISOLDE concerning the EBIS aim at reaching a throughput that exceeds \(10^{10}\) ions per second. The repetition rate of the EBIS and the Penning trap must be as high as possible. This in turn means that the charge breeding time of the EBIS has to be less than 10 ms, requiring electron beam current densities to be above 500 A/cm², especially for heavier radioactive ions. A Penning trap’s repetition time is limited by the cooling time and the centring time. Whether or not values shorter than 10 ms can be achieved has still to be investigated.

- Due to the large ECRIS plasma volume and the much higher ion density achievable in the plasma, the ECRIS should be able to accept higher intensities, up to \(10^{12}\) ions/s without efficiency losses. However, this is an important point which needs to be checked.

- Test measurements will be performed at the REXEBIS in order to determine and to enhance the injection efficiency. A single pass emittance improver like a gas filled Radio-Frequency-Quadrupole (RFQ)-ion guide [104, 105] could enhance the efficiency significantly, because a small injection emittance of the beam into the EBIS is required.

- A new ECRIS PHOENIX from ISN Grenoble is being developed with a flexible magnetic field configuration for confinement. This ion source is suitable for different microwave frequencies (14.5, 18 GHz) and has a new injection geometry optimized for high injection efficiencies. An improvement of injection efficiency, higher efficiency in individual charge states and breeding times below 50 ms for a larger variety of ion species are thus expected [106].

- The charge breeder is fed by dedicated low charge ion sources of radioactive beams, which have been optimized over many years for efficiency and selectivity. A typical example is the laser ion source where special isobaric or isomeric radioactive beams can be selected. Thus the charge breeder has to be matched to the emittance of the dedicated sources, which all are available at the large scale facility ISOLDE/CERN.

- An additional crucial element of the R&D work in the charge breeding business is a detailed comparison of the separation of the radioactive ions from contaminant ions arising from residual gas which are also produced in the charge breeding devices.

4.6.2 The linac as post-accelerator

The option of using a linac as a post-accelerator is suitable for several scenarios. Figure 4.18 shows either a low duty cycle linac, concerning charge breeding in pulsed mode, or a CW-linac in the continuous charge breeding mode. Using an EBIS as the charge breeding device, intrinsically a pulsed ion source, the linac duty cycle can be reduced significantly. This avoids high power RF-devices, cooling problems and superconducting structures. In the case of the ECRIS both a low duty cycle linac and a CW linac are possible because the ECRIS is able to deliver continuous beams as well as pulsed beams. The requirements of a linac for post-acceleration of radioactive ions are a final energy of 5–10 MeV/u with a low energy spread of about 0.2%, the possibility of energy variation and a covered mass range of 10–200 u. From these requirements different linac designs, shown in Fig. 4.20, can be considered.
A low duty cycle linac

In the case of a pulsed linac, the repetition rate and the length of the ion pulses coming from the charge breeding device should not exceed a duty cycle of more than 10%. In principle, such a post-accelerator represents an upgrade of the REX-ISOLDE linac [107]. The REX-ISOLDE linac is designed within a tuneable final energy of 0.8–2.2 MeV/u and is a prototype of a low duty cycle linac for RNB. The R&D work for low duty cycle linacs as post-accelerators at different final energies can be covered in the following topics.

- For the first section of a modern ion linac the Radio Frequency Quadrupole (RFQ) has proven the most suitable structure. The IH-RFQ [108] is a quadrupole structure driven by a cavity operating in the resonant $TE_{111}$-mode. Higher shunt impedances and easier handling of rod cooling in comparison to the well-known four-rod structure are the proposed features of the structure [109]. For the development of highly efficient driving structures for RFQ accelerators, the adoption of the IH-RFQ to higher frequencies seems to be the most suitable way forward.

- Accelerators with a high number of gaps are not flexible in the final energy. In order to get a variability in the final energy, resonators with a low number of gaps are necessary. Improvement of energy variable structures like the 7-gap resonators [110] using compact IH-structures and the $0^\circ$ synchronous particle structure to gain maximum energy variation are a central issue of future R&D work.

- In order to reach higher energies as in the REX-ISOLDE case, additional booster structures have to be inserted. To keep the number of cavities as low as possible, IH-structures are proposed using the combined $0^\circ$-synchronous particle structure [108], a novel beam dynamics concept, successfully in use at the GSI-HLI, and the CERN lead linac.

- In the higher frequency range (> 400 MHz) another kind of H-type structure is well suited, due to the cavity dimensions and the shunt impedance. This structure is the so-called cross bar H-structure (CH), which is driven in the resonant $TE_{211}$ mode [108]. The CH-structure is thus the drift tube accelerator counterpart of a four-vane RFQ which uses the same resonant cavity mode to load the vanes. A possible accelerator design with a final energy of 6–10 MeV using the CH-structure is shown in Fig. 4.20. This would be suitable for energies up to 10–15 MeV/u. Development of CH-structures for efficient acceleration in the high energy region, which have the advantage of higher operation frequencies and compact design,
are required for high energy compact ion linacs.

A CW-linac

The alternative post-accelerator is a continuous wave linac. This can be either normally-conducting, as at the ISAC project at TRIUMF [111], or superconducting like the Argonne linac [19] or the ALPI-Booster at Legnaro [112]. The latter is the solution adopted for the SIRIUS project. Superconducting structures avoid the cooling problems of a normally-conducting CW-structure, which is not a trivial problem.

The accelerator used at TRIUMF operates at the low frequency of 35 MHz because singly charged heavy ions are accelerated. Thus the cavities operating at this frequency are rather large and there is enough space for sufficient cooling with cooling jackets by using a split ring structure as driver of the quadrupoles. In order to accelerate highly charged ions from a charge breeding device, however, the cavity frequency must be above 100 MHz. This results in compact structures and massive cooling problems. An additional disadvantage of using normally-conducting CW-structures is the cost of high power transmitters running continuously.

Superconducting structures avoid cooling problems and the need of high-power amplifiers. Due to the its RF-power consumption a superconducting linac can be equipped with several one-gap cavities, which give maximum flexibility in the energy range of interest. Until now the first acceleration stage for a superconducting linac has been an electrostatic accelerator or a normally-conducting RFQ. At the INFN Laboratory in Legnaro a full niobium superconducting RFQ consisting of two cavities has been built and operated for the first time. This RFQ with a 4-rod design using stems 90° apart operates at 80 MHz and can reach up to 280 kV rod voltage. This demonstrates that it is now possible to build up a complete superconducting linac in all acceleration stages. Some R&D must be done to solve the problem of rod voltage flatness adjustment after assembly. Several superconducting resonators for the medium and high energy region, such as the four gap interdigital quarter wave resonator (IQWR) and the two gap quarter wave resonator (QWR) from Argonne, are well known and no additional R&D work is required. This solution has been adapted to the SIRIUS design.

4.6.3 The cyclotron as post-accelerator

Introduction

Cyclotrons represent a well documented and tested solution for heavy ion acceleration. References can be found in the conferences on cyclotrons, the last one being in Caen in 1998 [113].

In the context of the acceleration of radioactive beams cyclotrons have two very attractive features. Firstly, very high transmission may be achieved. With the CIME at GANIL for the SPIRAL project, for example, transmissions up to 50% have been obtained. Here the transmission is defined as the ratio of the ejected beam intensity to that at the exit of the ion source with an emittance of 80πmm*mrads [96].

Another very interesting feature of cyclotrons is the excellent m/q selection. Without any cooling of beams, resolutions of the order of 1 · 10⁻⁴ can be obtained without difficulty. This allows good m/q selection to be achieved without the supplementary loss of a high resolution separator.

The main disadvantage of a cyclotron with respect to linacs or tandems arises if frequent energy variations are necessary for excitation functions of some reactions, for example.

Transmission

One of the important features for radioactive beams is the transmission. The main critical points for transmission optimization are injection and ejection. With modern computer codes it is possible to calculate in detail, and with a very good degree of confidence, complicated field configurations that may optimize transmission.

Room temperature and superconducting cyclotrons

Up to 100 MeV/u (k=400) room temperature and cooled superconducting solutions are more
or less equivalent. The more compact size of a superconducting solution and lower operational costs are balanced by a worse separation of orbits, and in general no possibility of single turn ejection. This is a problem at very high intensity where the activation of the injection or the ejection system may be important.

Superconducting cyclotrons are at the moment successfully operated at KVI (Netherlands), LNS (Italy) and MSU (USA). For energies higher than about 100 MeV/u, the superconducting solution becomes more attractive due to size considerations. A project in this domain has been undertaken at GANIL, and one is under construction at RIKEN (Japan).

4.6.4 Possible developments

Cyclotrons are well understood accelerators and so in a standard configuration there is no need for a special R&D programme. If, however, there is a need to accelerate 1+ ions, then in order not to lose transmission a special design must be developed in order to give the possibility of accelerating ions with q/m values one order of magnitude lower than currently possible. Only a superconducting solution seems possible in order to achieve reasonable dimensions.

4.7 Recycling of Radioactive Beams with Energies at the Coulomb Barrier

Recycling of medium to low intensity radioactive beams after reaction in the target is very important because $10^2 - 10^3$ times larger luminosities can be built up, allowing low cross-section experiments to be performed. Even with thinner targets the same high luminosities of about $10^{30}/(cm^2s)$ can be achieved. Losses in the target by large angle Coulomb scattering, for example, limit the lifetimes of the beams, which must be comparable to the nuclear half-life of the radioactive beam nuclei. The width of the charge state distribution after atomic interactions of the beam ions in the target requires a large Q/p acceptance of the recycling ring. Furthermore, the energy loss in the target has to be compensated by a resonator. By correcting the arrival phase at the resonator field for the different charge states of the recycled ions via the path length, this energy loss is compensated independently of the charge state. Electron cooling may be exploited for cooling the emittance growth. The average number of turns made by the ions in the ring is much smaller, typically less than $10^6$, therefore recycling becomes more important than perfect storage. The recycling ring has elements of storage ring and accelerator physics but also those of experimental instrumentation. The achromat transporting the differently charged beam particles isochronously back to the resonator has properties of a large acceptance spectrometer. However, the acceptance for reaction products from the target also has to be optimized at the same time.

Many components of such a recycling ring have been already explored [114, 115]. However, until now such a ring for heavy ions has not been built. The required large acceptance in charge states ($\Delta Q/Q \leq \pm 20\%$) and phase space presents a real challenge. At the TSR storage ring (Heidelberg, Germany) multi-charge state operation was demonstrated with three beams of Cu$^{24+}$, Cu$^{25+}$ and Cu$^{26+}$ [115] and a rather large momentum acceptance of $\Delta p/p \leq \pm 4\%$.

Historically similar recycling schemes have been considered for charge state amplifiers [116, 117, 118, 120, 121]. Here ions after passing through a stripper yield a spectrum of charge states where only one charge state is selected for further acceleration. Nowadays ions with other charge states are recirculated to the stripper and the stripping-selecting process is repeated several times. By this method the stripping efficiency for the most abundant charge state can be increased by a factor of 4 at most. For recirculation, microtron-like set-ups [116] or storage rings [117, 118, 120] have been considered.

For recycled radioactive beams much larger increases of the yield by factors of 100–1000 are expected because the beam produces reaction products after each recycling. Here the most probable charge state is not extracted but is used repeatedly in the target.

The main requirement for a recycling storage ring is that the different charge states have
the same orbit length in the dipoles. This is necessary because all beam particles leaving the target have the same velocity, and therefore the same flight time to the resonator, when the orbit lengths are equal. The ring is isochronous. This means that a nondispersive region in the target is required and the resonator section has to be connected by two achromats. Such a set-up is shown in Fig. 4.21.

Figure 4.21: The recycling ring.

The shape of the polefaces of the dipoles, which are shown in the upper half of Fig. 4.21, can be determined easily by requiring that the orbit length for different charge states is the same in the dispersive region.

Required developments for recycling rings are:

- higher order corrections,
- magnet design,
- multi-charge state beam operation at different energies,
- study of chromaticity,
- mini-beta insertion,
- target design,
- efficient achromatic extraction of reaction products,
- coupling to cooled and pulsed beams delivered by traps and similar devices.

The following are typical experiments using compound nuclear reactions:

- Production of longer-lived superheavy elements:
  Here a typical reaction would be \(^{92}\text{Kr} + ^{208}\text{Pb} \rightarrow ^{298}118 + 2n\), which is similar to the reaction with stable \(^{80}\text{Kr}\) used in the first production of element 118.

- Study of new fusion reactions with doubly magic nuclei:
  For the reaction \(^{132}\text{Sn} + ^{132}\text{Sn} \rightarrow ^{262}2n\) we would try to use an ECR storage cell as radioactive target in the storage ring. Furthermore, the production of \(^{262}\text{Fm}\) would be of interest because one could follow the deformed magic number \(N=162\) to lighter nuclei.

- Excitation of giant resonances in reactions of nuclei with different N/Z-ratios:
  Here we could compare the giant resonance excitation probability for reactions between stable Kr isotopes and those with neutron rich isotopes e.g. \(^{91}\text{Kr} + ^{86}\text{Kr}\). Large NaI-detectors could be installed close to the target to study the giant resonances and a trigger with the produced recoiling compound nuclei could be used.

- Production of long-lived K-isomers, extending the known isomers in Hf-nuclei to more neutron rich isotopes.

4.8 Special Instrumentation

4.8.1 Overview

The advent of advanced facilities for exotic beams brings with it both enormous opportunities for exciting research and new nuclear
physics, and technical challenges of high order. The latter stem from the fact that many RNB intensities will be orders of magnitude lower than beams we are accustomed to. To understand the new data and new nuclei that we will have access to in this situation will require the development of specialized techniques (such as inverse kinematics), highly efficient detectors and mass separators, and new more efficient signatures of structure that can extract more structural information from less data. There are, nevertheless, lower limits for RNB intensities where certain observables discussed in Chapter 2 can be determined. They are shown in Fig. 4.22 together with the detector techniques outlined in this chapter. The aim of supplying a factor of a 10–1000 higher beam intensities with the next generation of RNB facilities can be justified by getting access to different new observables for many nuclei.

![Figure 4.22: Intensities, observables and techniques.](image)

Among the most important detectors will be high efficiency, high granularity, high resolution arrays of $\gamma$-ray detectors. The need for high efficiency is clear; the granularity will be needed in many cases to reduce Doppler effects in nuclear reactions. Good energy resolution is needed both because of the possibility of a high density of $\gamma$-lines in spectra that may contain data from many nuclei simultaneously and because of the enhancement in peak to background that accompanies high resolution. The possibility of large improvements in resolving power for high multiplicity events has recently arisen with the concepts of $\gamma$-ray energy tracking devices.

In conjunction with the present generation of Compton-suppressed $\gamma$-detector arrays, a variety of 4$\pi$-geometry charged particle detectors have been developed and used. Further development of such detectors incorporating special constraints and requirements for use with radioactive beams is also a recommended area of effort that could benefit from international workshops and collaborations. The same comments apply to related detectors, such as large-area, highly efficient neutron detector arrays.

Many varieties of research at next generation ISOL-type facilities requires the use of modern reaction-product recoil ion detectors. The development of a new type of broad-range, large acceptance magnetic spectrographs is also needed. Several types of such spectrographs could be developed and optimized for specific classes of research. Where medium-to-high resolution is required, it will be appropriate to use next-generation designs of classical magnetic spectrographs extended to much larger solid angles, of the order of 100 msr, in combination with good energy resolution and broad momentum range. Examples of this type of spectrograph are under development at GANIL, Legnaro, and Catania. A variant of this type of magnetic spectrograph is the gas-filled separator, one of which was recently constructed at Berkeley. Studies of designs that permit a single spectrograph to be operated optimally in various modes may lead to more cost effective, but still very capable devices. Other geometries, which might emphasize acceptance and range over resolution, are also conceivable. Examples of this class of device are large magnetic solenoids or multi-gap toroids for detecting the light ions from direct reaction studies with inverse kinematics. Further evolution of these designs towards a new generation of advanced spectrographs would be appropriate for an international study group.

Neutron detectors are also powerful ancillary systems in connection with neutron-emitting reaction channels. They are of vital importance for the study of neutron-rich nuclei, either to provide a trigger or for complete kinematics experiments. For these types of investigation good granularity with high overall efficiency is at a premium. The Franco-Belgian detector DE-
MON is a good example of such an array, and the LAND detector at GSI presents the state-of-the-art for relativistic neutrons.

Complementary detector systems, such as a high resolution $2\pi$ electron-solenoid in conjunction with a $2\pi$ Ge-shield, are also important investments for future nuclear spectroscopy studies.

A requirement for many future experiments with rare exotic beams is high beam quality, with low transverse and longitudinal emittance as well as the suppression of contaminants with very similar charge-to-mass ratios. A flexible variable time structure in the beam is also important. For these reasons the development of techniques for bunching, cooling, storing and purification with lasers, traps, radio-frequency and buffer gas methods, for example, is of vital importance for future success in nuclear physics and with potential applications in a number of different fields.

In the last few years there have been exciting new developments in many of the instrumental areas mentioned above and all have relevance for future RNB experiments. However, central to a successful RNB-programme will be the ability to detect rare events from large backgrounds created by the decay of the beams. The core of such a programme will require very efficient ejectile selection coupled to particle and $\gamma$-decay of the selected particle. Sections 4.8.2 and 4.8.3 give some details of magnetic and electromagnetic analysers for such particle selection, along with recent developments concerning $\gamma$-ray detection.

### 4.8.2 High efficiency $\gamma$-ray detector arrays

Gamma-ray detectors for RNB-work need to have high efficiencies, high granularities and high energy resolutions. The granularity will be needed in many cases to reduce the Doppler effects in nuclear reactions, to track gamma rays in order to distinguish total energy absorption events from Compton scattering and to handle $\beta$-decay induced backgrounds. The high energy resolution is needed both because of the possibility of a high density of gamma lines in spectra that may contain data from many nuclei simultaneously and from the enhancement in peak to background that accompanies high resolution. There currently exist a number of advanced arrays such as GAMMASPHERE and EUROBALL that are much more efficient than their predecessors. However, the possibility of new technology leading to a several orders of magnitude improvement in resolving power for high multiplicity events has recently arisen with the concept of gamma ray energy tracking devices.

In several places these new highly efficient germanium detector arrays (EXOGAM, MINIBALL, MARS, GRETA) whose individual detectors become position-sensitive by segmentation are being developed. Position information allows the individual interactions of $\gamma$-quanta to be identified and Compton scattering events to be reconstructed. Furthermore, a Doppler correction is performed for the $\gamma$-rays to improve the final energy resolution. Encapsulation of individual Ge-detectors is advantageous because it gives easy access to the front-end preamplifiers and recovery of performance by baking out the detectors after neutron damage can be easily accomplished.

EXOGAM, a European initiative, is a good example of these new developments. It is specifically aimed at a radioactive beam programme of the SPIRAL facility at GANIL. EXOGAM will consist of an array of high resolution germanium detectors. These will be arranged to give a high photo-peak efficiency of $\geq 20\%$ for 1.3 MeV gamma-rays. Very high efficiency is required since the beam intensity, at least at the start up of the SPIRAL facility, is expected to be much lower than with stable beams, a factor of 100 or even 1000 lower in many cases of interest.

Segmented CLOVER detectors will be used in the array to give the optimum coverage approaching $4\pi$ and optimum performance in a radioactive beam environment. Segmentation is required to provide the optimum performance in terms of efficiency, energy resolution for $\gamma$ rays from recoiling reaction products, and minimiza-
tion of multiple-hit events. These Ge detectors will be separated by BGO suppression shields.

The electronics system to process energy and timing information, make trigger decisions and relay data onto an acquisition system will be based on the VXI and VME standards. It will comprise purpose built VXI cards for the new detectors, and a dedicated data acquisition system capable of recording data up to 2 Mbyte/s. The new VXI electronics is designed to be compatible with pulse shape analysis, a part of the project which is still in the R&D domain. Figure 4.23 gives a schematic diagram of EXOGAM.

![EXOGAM array with 16 Ge detectors](image)

Figure 4.23: The EXOGAM array with 16 Ge detectors.

An exciting new development in $\gamma$-detector technology is the prospect of tracking the path of $\gamma$-rays through the Ge stopping material. This new electronic segmentation has considerable potential but as yet is still in the early stages of development. Substantial R&D is needed to further this technology, and indeed work in this direction is currently under way in both America and Europe. This is an ideal area where extensive international collaboration would benefit the development of a nuclear physics research capability that would be an important advance for all involved. Additionally, the extension of double-sided silicon strip detector technology to germanium crystals is an area for potentially fruitful development.

### 4.8.3 Magnetic and electromagnetic particle analysers

**Recoil detectors**

A variety of research at ISOL-type radioactive beam facilities requires the use of modern reaction product recoil ion detectors. These devices are especially important for proton and alpha capture reactions at very low energies needed for nuclear astrophysics cross-section measurements for compound nucleus studies involving weak reaction channels or stronger channels with low beam intensities. Many of these studies with radioactive beams will have to use inverse reaction kinematics and often gas targets as well. A new recoil separator, DRAGON, for capture reactions and an associated gas target are under construction in Canada for use at the ISAC facility at TRIUMF. International collaboration on the design and optimization of both capture and fusion reaction separators for the next generation facilities is encouraged.

Another type of recoil separator, the gas filled recoil separator, is efficient at separating heavy fusion products from target or projectile like fragments. Fusion products emerging from the target have a wide charge state distribution, but if such ejectiles pass through a magnetic dispersive element then they will follow a trajectory determined by the average charge state of the ejectile as it passes through the gas. This type of separator has a high transmission and a good suppression from the primary beam, at least for intermediate projectile mass and target. Where the beam is an RNB these are attractive features enabling experiments on fused heavy products away from the decay site of the beam.
Large solid angle, broad momentum acceptance spectrographs

The low intensity of secondary beams requires very efficient detection devices. As far as the detection of light charged particles is concerned, multistrip Si-devices such as LEDA, MUST and similar devices are already used in experiments. These devices are well suited for detecting either light recoil particles in inverse kinematics, such as $(p,p')$ or $(d,p)$ reactions for example. However, information is very often needed on the heavy mass projectiles. This demands a good resolution measurement of the mass, the velocity and the atomic number of outgoing reaction particles. A typical experiment would be the study of $\gamma$-rays in a collision of a nucleus of the secondary beam with a target nucleus. Very efficient and unambiguous tagging will be necessary in order to know which reaction product was at the origin of the $\gamma$ ray observed.

Most intense RNBs are at the moment obtained with light ions such as $^6$He, $^8$He and $^{11}$Li. So even with quite light targets, recoil velocities will be low and it will be difficult or impossible using gas or solid state detectors of reasonable area to achieve the necessary resolution. This is why the development and construction of a new generation of very high solid angle large momentum acceptance spectrometers is currently under way. The solid angle that is aimed at is in the region of 100 msr, as compared to classical spectrometers (Speg, Lise, Rips), that have solid angles in the domain of 1–10 msr. However, this big solid angle is paid for by the fact that it is no longer possible to achieve high resolution through the spectrometer's properties alone. Large acceptance implies that higher order aberrations become dominant and they can no longer be corrected by multipole elements. High resolution is instead obtained by ray-reconstruction, for example the measurement of the particle trajectories allows reconstruction of the particle kinematics and properties. For very low recoil energies this requires the development of a new generation of detectors that give a very low perturbation of the particle trajectories and hence need to be very thin, in the range of 0.01 to 1 mg/cm$^2$. The spectrometers described below are two examples and are selected here for illustrative purposes only. There are various other projects world-wide as well as in Europe. A workshop on such devices for the US radioactive beam facilities was held in spring 1998.

![Figure 4.24: The MAGNEX spectrometer: Horizontal (top) and vertical (bottom) trajectories through the spectrometer obtained with COSY INFINITY.](image)

- MAGNEX (a large acceptance MAGNetic spectrometer for EXcyt) will be constructed at the LNS at Catania, Italy. It has a quadrupole dipole structure. The dipole contains strong multipole components. It uses the measurement of particle trajectories at the entrance of the spectrometer and a focal plane detector for ray reconstruction. MAGNEX is optimized for the study of direct reactions induced by secondary beams.

- VAMOS (VAriable MOde Spectrometer) is under construction at GANIL. It has a QQFD structure, where F stands for Wien-filter. This combination allows VAMOS to
work in different optical modes: a large solid angle nondispersive mode, a Wien-filter mode, a mass-spectrometer mode and a dispersive mode similar to the preceding spectrometers. VAMOS is optimized as an instrument for tagging in coincidence experiments.

As a general point the development of this area is only limited by imagination, and of course finance. Other possible geometries are conceivable, each emphasizing a particular advantageous measurement parameter. For example, a class of devices that trades acceptance angle over resolution, includes large magnetic solenoids or multi-gap toroids for detecting the light ions from direct reactions studied with inverse kinematics. Further evolution of these designs towards a new generation of advanced spectrographs would be appropriate for an international study group.

**Efficient focal plane detectors**

For high-transmission recoil separators a special tagging detector system has to be deployed at the focal planes. This must be highly segmented, provide excellent energy resolution and have the highest possible efficiency. Furthermore, the large number of individual detectors must be read out at high rates and the events of interest selected according to the temporal and spatial associations dictated by the physics of the experiment without incurring unacceptable data losses. As an example of a detector system satisfying these criteria the GREAT spectrometer is shown in Fig. 4.25.

4.8.4 Efficient stopping, cooling and trapping of rare reaction products for precision experiments

For a detailed and precise investigation of rare products from reactions with radioactive beams it is advantageous to slow them down to very low energies and finally to bring them to rest in ion or atom traps where they can be studied during their remaining lifetime. Important experimental opportunities are:

- highly accurate mass measurements,
- high efficiency and precision decay studies,
- laser spectroscopic investigations,
- ion chemistry studies.

![Diagram of GREAT spectrometer](image)

Figure 4.25: Scheme of the GREAT spectrometer to be positioned at the focal plane of recoil separators such as RITU or SHIP. The blue shaded regions represent silicon detectors, the green shaded regions germanium detectors. For clarity, the multiwire proportional counter (magenta), through which the recoils pass, is not shown in the upper figure.

The key that enables such studies is a good scheme for the reduction of the energy of the reaction products from typically several MeV to less than eV and for the appropriate beam manipulation and trapping schemes:

- a very high efficiency is required in the slowing-down and trapping processes in order not to lose the minute quantities of rare species,
- the whole process has to be fast (ms) since decay losses in the case of very short-lived isotopes can not be tolerated,
- the scheme should have no constraints concerning the elements that can be studied,
- via dedicated beam manipulation and trapping schemes cold clouds of a single selected reaction product have to be prepared.
One concept presently followed at several places around the world seems to be the most promising for slowing down reaction products and transforming them into a low energy, low emittance (pulsed) ion beam. Mass separated reaction products are completely stopped in a buffer gas cell. If helium is used a larger fraction of them survives in a 1+ charge state. On the other hand, neutralized species may be reionized in the gas cell by resonant laser ionization, which can be directly used as a spectroscopic tool. The ions are quickly guided towards the exit nozzle of the cell by electrostatic or radio-frequency fields, or a combination of the two. After passing the nozzle the ions are injected into a radio-frequency ion-guide system that provides transverse confinement of the ions. Here, the gas is removed by efficient pumping in differential pumping sections and the ions are guided into a low pressure region. In most of the designs presently under study a longitudinal guiding field allows the speed of the ions through the system to be maximized. The ions can be either extracted as a continuous ion beam or as pulses, in both cases with excellent beam quality. For pulsed-beam production the ions are first accumulated and then released by appropriate switching of electrode potentials at the end of the ion guide system. These ion bunches can then either be sent to further ion traps for purification if required or directly to experiments for the actual measurements. From the experience with presently existing gas stopping cells, ion guides and linear traps overall efficiencies of 10% are realistic, as well as transfer times of < 10 ms.

For mass measurements and decay studies it is particularly important that only the species that should be investigated are delivered. Therefore an additional purification of the low energy beam will often be required. This could either be achieved by means of conventional magnetic separation or, if very high selectivity is required, by operating a Penning trap as high resolution mass separator. Such a scheme has been in successful operation for many years at ISOLDE within the ISOLTRAP experiment. Resolving powers of $R = 10^5$ have been achieved.

For mass measurements Penning traps have been proven to provide very high resolving power and accuracy. For medium mass ions resolving powers of $R = 10^7$ in the cyclotron frequency determination and accuracies of $\Delta m/m = 10^{-8}$ can be achieved. However, one specific feature of Penning traps should be noted: the achievable resolving power is directly proportional to the storage time $T$ of the ions in the trap and the quoted figure corresponds to $T > 10$ s for singly charged mass 100 ions in a $B = 7$ T magnetic field. Hence, short-lived and heavier isotopes can be studied only at the expense of resolving power. There are two scenarios of improvement. One is the use of highly charged ions, in this case further losses in the charge breeding process must be envisaged. The other is to use higher harmonics in the cyclotron frequency determination. Such a scheme is planned to be tested at ISOLTRAP at CERN.

For the investigation of the chemical properties of transactinide elements atom-reaction studies in the gas-phase are important. Such studies could be performed by combining a trap in which the reaction takes place with a Penning trap mass spectrometer.

The possibility of having radioactive ions confined backing free in space is interesting for a number of precision decay experiments, for example electron-neutrino, or other correlation studies, and conversion electron spectroscopy as well as for spontaneous fission studies. Ion traps for decay studies require different designs compared to those used for mass measurements. In general they will be quite open systems in order to allow an efficient 4\pi detection of the decay products and their design has to match the requirements of the detector systems. On the other hand their demand on the field quality is not high and several of these systems may be affordable.

For some experiments one may even consider storing the reaction products not in ion traps but in atom traps. Experiments of interest here could be atomic parity non-conservation experiments on very heavy systems where these effects are largely enhanced, and precise $\beta$-decay and correlation experiments for fundamental tests.
The availability of low energy ion beams will also be of importance here since they can be brought into the neutralizers of the atom trap systems with very high efficiency.

One example of a system in which rare reaction products are brought to rest and trapped as discussed above is SHIPTRAP being built at GSI. The layout of the SHIPTRAP system is shown in Fig. 4.26. Here recoil ions from fusion evaporation reactions are separated and delivered by the Wien-filter SHIP. A device similar to SHIPTRAP is under design for the forthcoming Munich fission fragment accelerator facility. At GSI, and in future at Munich, the investigation of superheavy elements is of particular interest. Another device termed JYFLTRAP, connected to the IGISOL-type on-line mass separator consisting of an ion-cooler coupled to a Penning trap identical to the SHIPTRAP, is under construction at Jyväskylä with a special emphasis on studies of short-lived exotic nuclei of refractory elements. At KVI–Groningen a similar device (TRImuP) will be used to set up a user facility for fundamental physics studies.

Figure 4.26: Set-up of the SHIPTRAP facility. It consists of a stopping gas cell for the SHIP reaction products, a radio-frequency ion guide and trap system, and a tandem Penning trap system.

SHIPTRAP consists of a stopping chamber containing the noble gas, an extraction system to separate the gas from the ions and to guide the thermalized ions into a vacuum region, a preliminary trapping and guiding system to collect the ions in this vacuum region and to cool them into well defined bunches, a purification trap for isobaric separation and a precision trap, both placed in the same superconducting magnet. The first Penning trap accumulates the ion bunches, filters out possible contaminants and further cools the collection to room temperature. This collection is then either extracted on the demand of downstream experiments or captured in the second, precision Penning trap for direct mass measurements.

There is a number of key experiments that can be carried out with SHIPTRAP, MAFFTRAP and similar facilities to come. Some of them are discussed below.

The exploration of nuclear binding energies of superheavies and transactinides will allow the impact of shell stabilization on these heavy systems to be studied in detail and with high accuracy. The expected long half-lives close to the islands of enhanced stability may even prohibit the present-day identification via α-decay chains and require a direct mass analysis. Proton-rich isotopes produced in fusion evaporation reactions with lighter ions can be investigated in order to perform a precise mapping of shell effects close to the self-conjugated nucleus $^{100}$Sn, to study the p-n interaction for heavier $N=Z$ isotopes, or to deliver precise Q-values for fundamental tests. In the case of very neutron-rich isotopes produced via fission the important effect of shell quenching far from stability and the onset of new shell closures may be explored.

Laser spectroscopy gives access to the determination of nuclear moments and charge radii via the measurement of hyperfine structure splittings and isotopic shifts. In particular, for very heavy nuclei the unusual nucleon density distributions are predicted that may be probed. Laser spectroscopy will not only play an important role in answering nuclear physics questions but also reveal new atomic properties. In the case of transactinides relativistic effects play an important role in determining the atomic level structure. But hardly any information exists to date - for fermium (Z=100) even the ionization potential is unknown. Such laser studies can, with low resolution, be carried out directly in the gas cell via multi-step resonance ionization.
Decay studies in traps would have the advantage that the source would be completely free of absorption and back-scattering problems and that efficient $4\pi$ detection of all products could be easily realized. Experiments might range from coincidence experiments such as $\beta$-delayed particle emission studies to high resolution conversion electron spectroscopy and fission studies. In particular, in the trans-actinide region electron capture and internal conversion are often the dominating nuclear decay processes and their study allows for spin and parity determinations. A careful study of fission will give a deeper insight into the nuclear dynamics of very heavy nuclei. The determination of the energetics of the products of a spontaneously fissioning nucleus stored in a trap between two detectors will be become possible for the first time.

Certainly of great interest, but also extraordinarily challenging and a long-term goal will be the study of atomic parity conservation in very heavy systems. These offer the advantage that PNC effects are largely enhanced by a factor $> 2^3$. The most precise experiments have so far been carried out on caesium ($Z=55$) and the results already indicate physics beyond the standard model. The heaviest element presently considered for such studies is francium ($Z=87$). Such experiments can in principle be carried out in atomic traps. A pre-requisite is a detailed knowledge of the atomic level scheme of the chosen element.
5. In-Flight Facilities: Physics with Exotic Nuclear Beams

5.1 The Present Situation

The in-flight method has been very successful for the investigation of exotic nuclei from low energies near the Coulomb barrier up to relativistic energies far above the Fermi energy [122]. The method is well established for the investigation of short-lived nuclei at the limits of stability down to a sensitivity of a single atom.

Highlights in physics at the Coulomb barrier are the discoveries of the heaviest known elements and of ground state proton radioactivity, both produced by complete fusion. Fusion reactions lead to low-energy recoils appropriate for decay studies after in-flight separation.

The in-flight method applied to relativistic energies, which is the main subject of this report, has opened up new fields of research since intense high-energy heavy-ion beams from 50 MeV/u to 1 GeV/u became available for reaction studies [123]. With fragmentation of energetic heavy ions in peripheral nuclear collisions, beams of exotic nuclei at energies far above the nuclear interaction barrier could be produced for the first time. Reaction studies with exotic nuclear beams have allowed us to gain new information on the structure of nuclei far off stability, complementary to that obtained from decay studies. In these pioneering experiments, new far-off-stability regions of the chart of nuclei have already been explored. In fact the discovery of completely new phenomena, for example nuclear halos in light nuclei such as $^{11}$Li, $^{11}$Be and $^8$B at and near the neutron and proton driplines gave rise to the recent rapid development in experimental and theoretical nuclear structure physics [1].

New experimental methods were developed. Break-up studies gave access to the wave function and momentum distribution of halo nucleons, as well as direct access to many-body interactions not accessible in conventional scattering experiments exploring only binary encounters. The first generation of reaction studies with light nuclei has already contributed to a new understanding of nuclear matter in the transition region from bound to unbound states, the interaction with the continuum, nucleon-nucleon correlation and many body forces. Fission in-flight of unstable actinides, produced by fragmentation, allowed systematic studies of their fission-fragment distribution for the first time. Moreover, the application of the storage-ring technique to exotic nuclei has already permitted the extension of the number of known masses by 10% in the first experiments.

At present, a number of fragmentation facilities exists in Europe at Dubna (Russia), GANIL (France) and GSI (Germany). These cover energies from 30 MeV/u to 1 GeV/u as shown in Fig. 5.1. On the international scale MSU (USA), RIKEN (Japan) and a facility at Lanzhou (China) must be added to this list [126].

A new method for secondary beam production is the fission in-flight of relativistic uranium beams. Fragmentation and fission are complementary production methods. While the fragmentation process populates the region of nuclides in the ‘spallation corridor’, which runs parallel to the valley of stability but shifted slightly to the proton-rich nuclides with highest intensities, fission creates neutron-rich fragments centred around tin and krypton as shown in Fig. 5.2.

Fragment beams of all elements of the periodic table including uranium have been produced, separated by A and Z, and used for experiments. In the series of exploratory ex-
periments a number of exciting discoveries and key experiments for future research programmes have already been made. These include the discovery of the three doubly magic nuclei, $^{100}$Sn, $^{78}$Ni and $^{48}$Ni, together with the discovery of about 120 neutron rich isotopes in the range from ytterbium to palladium, and the precise measurement of the mass surface of the neutron-deficient region from lanthanum to uranium, including 165 nuclides with unknown masses [124].

There are four main classes of nuclear physics experiments characterized by:

- decay studies,
- reaction studies,
- precision experiments with cooled beams in heavy ion storage rings,
- structure studies in low-energy heavy-ion – electron colliders.

Figure 5.1: Energy and Z range of secondary beams for existing and planned exotic nuclear beam facilities. The Coulomb barrier and the energy needed to provide bare (90%) nuclei emerging from the production target are indicated.
Decay studies are primarily performed with separated mono-isotopic beams or selected beam cocktails where the individual nucleus’s mass and nuclear charge are identified in-flight event-by-event. The short separation time of microseconds, sensitivity to single atoms and clean separation are characteristics of the in-flight method. Fragment separators are therefore ideal tools for accessing the most exotic nuclear species at the limits of stability.

Reaction studies in the high-energy regime generally use thick targets thus providing sufficient luminosity even for low beam intensity. Kinematical focusing of the fragments allows $4\pi$-detector geometry for all reaction products. The study of nuclear break-up, including heavy fragment, proton, neutron and gamma measurements including their kinematical properties and angular distributions is a rich and fast developing field.

Nuclear physics studies with heavy ions in storage rings [125] are still in an exploratory stage. However, storage and cooling yield interesting new features, for example brilliant beams of the highest phase-space density and nuclei in exotic atomic and nuclear states (bare and few electron systems, isomers). To date, only experiments on nuclear mass and half-lives have opened the field of investigations with stored exotic nuclei. The results clearly demonstrate the large potential of storage-ring experiments in terms of high precision and new effects such
as the influence of electron density on nuclear $\beta$-decay. The simultaneous observation of mother and daughter ensembles up to few ions can yield new basic information about nuclear decay. The decay of single atoms observed in the storage ring will also provide new insights. With the experimental discovery of bound-state $\beta$-decay for the first time, reaction and decay conditions that prevail in the stellar environment have been realized in the terrestrial laboratory. The excellent mass resolution of 650,000 achieved for cooled fragment beams in the ESR opens also a new field for experiments with isomeric beams.

Structure studies of exotic nuclei with electron scattering in small colliders are presently under discussion and still in the R&D stage.

5.1.1 Characteristics of the in-flight method

High-energy reactions are advantageous for theoretical nuclear structure studies because the movement of nucleons is negligible during the collision time (the so-called sudden approximation). Therefore, at high energies the colliding nuclei can be considered as frozen systems, in other words, the experiment yields a ‘snapshot’ of the nucleons in momentum space.

Projectile fragmentation and fission in-flight provide relativistic beams of exotic nuclei along the entire periodic table up to uranium, irrespective of their chemical properties and with half-lives down to microseconds. The fragments emerge from the reaction target with the kinematical properties of the primary beam, modified by the reaction kinematics. Enlargement of the emittance is caused by momentum transfer from removed nucleons in the fragmentation process or by the total kinetic energy released in the fission process.

Clean mono-isotopic separation is achieved by magnetic rigidity analysis combined with energy loss in shaped matter assuming that the fragments are fully stripped. The condition that all isotopes are bare contributes to an efficient separation and transport of the reaction products. The electron stripping condition determines the minimum beam energy and access to beams of heavy elements (see Fig. 5.1). Optionally, beam cocktails of well defined composition can be provided.

Advantages of the high-energy in-flight technique are:

- high separation efficiency for all elements irrespective of chemical properties
- sensitivity down to single atoms,
- short separation times of less than microseconds,
- high luminosity even for low intensity beams by the use of thick targets for production and reaction studies,
- kinematical focusing allowing for efficient injection into separators, beam lines and storage rings,
- full solid angle coverage for reaction studies,
- unambiguous $Z$-identification due to high particle velocities,
- high efficiency neutron detection by shower recognition,
- and the option for beam cocktails allows a number of neighboured nuclides to be investigated at the same time with the advantages of an efficient use of the beam and simultaneous measurements of reference-nuclei and reactions.

A disadvantage is the low phase-space density of the fragment beams. However, the phase-space density can be enhanced by increasing the beam energy. Beams of the highest brilliance with relative momentum spreads of less than $10^{-6}$ and transverse emittances of below 0.1 $\pi$mm mrad are created by electron cooling in a storage ring.

All these different aspects lead to the conclusion that the energy of 1 GeV/u is optimal for a next generation in-flight facility. In fact, it covers an energy range with unique possibilities for reaction studies, complementary to ISOL and low-energy fragmentation.
5.2 The Next Generation Large Scale In-Flight Facility

New experimental efforts are required to move closer to the extreme limits of stability. Prerequisites for such efforts are increased beam intensities and the development of new experimental methods. Such activities are in progress at GSI and MSU as well as at RIKEN with its new projects including a storage-ring complex with a heavy-ion–electron collider [127]. A combined ISOL and fragmentation facility is proposed in the framework of an advanced radioactive beam facility in the US, RIA.

The next generation large scale fragmentation facility for Europe has been discussed in two working groups in November and December 1998 [127, 128]. Their brief was to outline the experimental programme and to select the appropriate accelerator. The ideas and conclusions from these workshops form the basis for this part of the report. Results from the discussions at GSI are also included here.

The new in-flight facility should provide:

- primary beam intensities of $2 \times 10^{12}$/$s$ for
- all elements from hydrogen to uranium with
- energies up to 1 GeV/u.

Its instrumentation should include the following items.

- A large acceptance fragment separator with an acceptance to separate fission fragments with efficiencies in excess of 50%. The required acceptance is $\pm 30$ mr in angle and $\pm 2.5\%$ in momentum. A new separator concept for high count rates and efficient background suppression should be considered.
- A new set-up for reaction studies with $4\pi$-detectors for complete kinematics and in-beam gamma and particle spectroscopy.
- A $\gamma$-ray tracking detector with a photo peak efficiency larger than 30%.
- An in-flight trap for separated fragments.
- A storage-cooler ring system comprising an accumulator and cooler ring for optimum storage of secondary beams.
- Fast stacking and cooling for short-lived species.
- An internal gas target for in-ring reaction studies of high precision.
- A power laser system for hyperfine studies at low beam intensities.
- An electron–heavy-ion collider with 40 MeV to 1 GeV centre-of-mass energy and a luminosity in excess of $10^{26}$ cm$^{-2}$s$^{-1}$.

5.2.1 Accelerator scenario

The maximum intensities for the various heavy-ion accelerators with 1 GeV/u uranium projectiles as the benchmark beam are:

- superconducting linac $10^{13}$/s continuous beam;
- cyclotron $10^{12}$/s continuous beam;
- synchrotron $2 \times 10^{12}$/s beam, repetition rate 1 Hz to 10 Hz.

The domain and competitiveness of such a next generation high-energy facility will clearly be heavy fragment beams and uranium in-flight fission allowing very neutron-rich species to be accessed.

There are two conflicting requirements for the time structure of the driver accelerator, determined by the research programme. In-flight particle identification and in-beam experiments ideally require a high intensity DC beam. A superconducting linac, a cyclotron or a synchrotron can meet the requirement. Storage-ring experiments, on the other hand, require short bunches appropriate for fast injection with repetition rates of a few per second to allow for efficient injection and stacking. A universal DC injection scenario is not available at present.

The conclusion is that a synchrotron is an appropriate driver that can efficiently be matched to the operation cycles of the storage
ring and can serve in slow extraction modes the reaction and decay studies performed directly at a fragment separator.

The currents for light projectiles are limited by the ion source. New high-current sources or funnelling techniques would enable further increases in beam intensity. For heavy elements above xenon, low charge state acceleration is needed to cope with space-charge problems. The acceleration of low charge states to high energies requires synchrotrons of large magnetic rigidity. A possible accelerator scheme of a next generation in-flight facility is shown in Fig. 5.3. A high-current ion source delivers the primary beam to a linac injecting into the driver synchrotron. The ions are accelerated to several hundred MeV/u, then stripped and injected into an accumulator which accelerates up to the final energy of 1 GeV/u for uranium. Electron stripping at high energies efficiently populates high charge states with a narrow charge distribution and thus reduces intensity losses. The accumulator could optimally match the conditions for reaction experiments and for storage-ring experiments due to a higher flexibility of the operating cycles.

Figure 5.3: Schematic of a next-generation in-flight facility, including the option of Rare Isotope (RI) acceleration.

The emittance of the primary beam for fast and slow extraction should not exceed 5 πnm m rad to allow the operation of high-resolution fragment separators and phase-space compression at the production target with ion optical methods.

A problem not yet solved is the efficient production of intense synchrotron beams from expensive rare isotopes. For instance, $^{48}$Ca or $^{38}$S are needed to access neutron-rich light nuclides. For the synchrotron, the development of high-temperature superconducting magnets is under discussion.

The expected yields of exotic nuclei can be reliably predicted because much experimental information is available. The beam intensities for a number of elements selected by NuPECC are displayed in Fig. 5.4. The rates given for the in-flight method include all possible reactions, uranium fragmentation and fission, and the production targets are beryllium of 4 g/cm$^2$ for fragmentation and of 2 g/cm$^2$ for fission.

![Yield vs Mass Number](image)

Figure 5.4: Yields of exotic nuclei produced with the in-flight method using projectile fragmentation and uranium fission in-flight at 1 GeV/u with projectile beams of $2 \times 10^{12}$/s. The region of stable beams, indicated by vertical dashed lines, is excluded.

The yield curves show secondary-beam intensities up to $10^{10}$/s close to stability and extending well into the proton- and neutron-rich regions far-off stability with intensities of more than $10^4$/s. The doubly magic nuclei $^{100}$Sn,
$^{78}$Ni can be produced with rates of 2 atoms/s (see Table 5.1), while the recently discovered nucleus $^{48}$Ni would be produced with the rate of 4 atoms/h.

Table 5.1: Production yields for doubly magic nuclei.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Production</th>
<th>Rate at the Detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ni</td>
<td>$^{58}$Ni fragmentation</td>
<td>4/h</td>
</tr>
<tr>
<td>$^{50}$Ni</td>
<td>$^{58}$Ni fragmentation</td>
<td>$7 \times 10^8$/s</td>
</tr>
<tr>
<td>$^{78}$Ni</td>
<td>$^{238}$U fission</td>
<td>2/s</td>
</tr>
<tr>
<td>$^{100}$Sn</td>
<td>$^{124}$Xe fragmentation</td>
<td>2/s</td>
</tr>
<tr>
<td>$^{132}$Sn</td>
<td>$^{238}$U fission</td>
<td>$6 \times 10^8$/s</td>
</tr>
</tbody>
</table>

The yield curves show the specific strength of the next generation European fragmentation facility. Uranium projectile fragmentation and in-flight fission will play a crucial role in accessing heavy and neutron-rich nuclei. The latter is of specific interest for structure research and astrophysics, as outlined in Chapter 2 of this report. The unexplored neutron-rich region near the double shell closure at $^{208}$Pb, not included in the yield curves, will become accessible too. In this context it is noteworthy to point out that phenomenological mean-field theories use nuclei with closed and doubly closed shells as reference systems. Hence high quality data in the vicinity of such nuclei as, for example, $^{208}$Pb will allow the theoretical input, especially for isovector, spin-orbit and pairing interactions to be tested and improved. For stringent tests of theories, either mean-field or many-body shell model approaches, measurements covering the full range of nuclides from the proton to the neutron dripline are required. The nickel chain from $^{78}$Ni to $^{48}$Ni could provide such a most valuable reference sample, for example.

The advantages of both ISOL techniques and in-flight fragmentation are combined in one scenario presently under discussion. Mono-isotopic beams produced in projectile fragmentation and fission reactions are separated in-flight and slowed down in a gas cell for trapping experiments and post-acceleration for low-energy experiments, requiring high beam quality, such as nuclear astrophysics and near Coulomb-barrier experiments. This scenario will be discussed in Section 5.3.1.

Physics in the low-energy domain, from the Coulomb barrier up to Fermi energies, can be well addressed by the high-energy fragmentation scenario as well. Schemes to decelerate projectile fragments to the Coulomb barrier are deceleration in a cooler and storage ring, and fast slowing down via atomic collisions of mono-isotopic fragment beams separated in-flight.

5.2.2 Target development

In the limiting fragmentation regime, the target material has no influence on the isotopic distribution of the secondary products as has been shown experimentally. For efficient conversion of the projectile beam, with a large number of nuclear interactions per unit of energy loss, light targets such as beryllium are preferable for fragmentation. Electromagnetic dissociation requires heavy targets such as lead but only plays a role for secondary-beam production close to the primary beam (few nucleon removal) and in-flight fission. The development of fragmentation targets for DC uranium beams of $10^{12}$ particles/s is not a problem in view of the heat deposition of just 12 kW.

The fast extraction mode needs investigation. For a bunch length of $10^{-4}$ s the beam load would be of 120 MW. A repetition rate of 10 Hz is preferable to rates of 1 Hz in order to reduce the energy deposition per bunch. Liquid targets such as lithium are under discussion. One method to reduce the point-heating of the target would be a fast achromatic sweeper using a magnetic kicker system. Further experimental studies and computer simulations are needed for efficient target development.

5.2.3 Beam formation and separation

To obtain fragment beams of high phase-space density, the projectile beam is focused to a small beam spot of about 1 mm diameter to create a fragment source of high brilliance. Phase-space enlargement due to the reaction kinematics can be minimized if the ion-optical condenser
method is applied. At intermediate energy such a device, based on superconducting solenoids, is installed at GANIL and has improved the secondary beam intensity by about a factor of 50. A similar principle should also be applied at relativistic energies, as shown in Fig. 5.5. However, it should be constructed with quadrupole magnets instead of solenoids. The beam spot size is essentially preserved over the full target length of 40 mm if the emittance of the projectile is sufficiently small; below 5 πmm mrad.

![Condenser Principle](image)

Figure 5.5: Principle of an optical condenser system at the production target: Phase-space enlargement after the production target without using a condenser (upper panel), with condenser (lower panel).

The handling of the activated target region needs investigation. It seems, however, not to present a major problem since the activation is localized in the fragmentation target and the major part of the beam intensity is dumped in the large dipoles. The energetic neutrons released from the projectile fragmentation, however, would require thick shielding in the beam direction.

The fragment separator is the key instrument in determining the quality of an in-flight facility in terms of transport efficiency, resolution and beam purity. It has been demonstrated that a well designed separator can be operated as:

- a high-resolution separator collecting and separating the fragments to inject them into the beam lines leading to the various experimental set-ups,
- an energy-loss spectrometer or as a dispersive system of high momentum resolution,
- a low resolution beam transport of high efficiency for secondary-particle beams such as pions or antiprotons.

To fully profit from the increased primary beam intensities, especially for uranium beams, a next-generation fragment separator must:

- transport projectile and fission fragments with high efficiencies close to 50%,
- separate the most exotic nuclei,
- and have in-flight detector systems to handle particle tracking and identification in a large dynamic range.

The fragment separator FRS at GSI currently reaches the transmission requirement only partially. For projectile fragments, the transport efficiency is 50% or more whereas for 1 GeV/u uranium fission fragments the corresponding efficiency is about a factor of 10 lower. To meet the benchmark, as defined by the NuPECC working group (acceptances of ±30 mrad in angle and ±2.5% in momentum) large-acceptance systems need to be developed. The application of these systems to relativistic beams of high rigidity, typically 18 Tm, needs compact superconducting lenses of high bending power which do not yet exist. Large-aperture superconducting quadrupole magnets seem to offer the most promising solution. A question still open is the number of separation stages of next generation systems. The currently used four-stage system with one degrader may not be sufficient. This design question is closely connected to the availability of detection systems for in-flight particle tracking and identification at high rates, and also to implantation experiments.
Modern fragment separators are operated in two principal modes. In one mode, mono-isotopic beams are separated by a successive and combined magnetic-rigidity analysis in front of and behind a shaped energy degrader (see Fig. 5.6). To provide isotopic separation up to uranium, a momentum resolution of 3000 is required. The homogeneity of the degrader must be of equivalent precision. In the second mode, the preparation of beam cocktails of a well defined A-Z region of isotopes is provided by an appropriate choice of degrader thickness and shape. Particle detectors trace the trajectory of each particle through a dispersive ion-optical system to measure its momentum, and combined with velocity measurements A/Z is determined. Z-determination is achieved with multi-sampling ionization chambers or silicon arrays. This mode is used for moderate count rates, determined by the capabilities of the detection system. It is also used for survey experiments such as the determination of interaction radii, nuclear break-up reactions and decay studies. Because it permits simultaneous investigation instead of sequential experiments this mode is ideally used for studies of fission fragment distributions as a function of the neutron number in the mother nuclei and shell strengths far-off stability.

![Figure 5.6: Schematic of the fragment separator, FRS, with tracking and particle identification detectors.](image)

A combination of a projectile fragment separator with a complete slowing down scenario in a gas cell is presently under discussion as a branch in the next-generation facilities (NuPECC-meeting December 1998). The fast slowing down of mono-isotopically separated fragment beams opens up new experimental opportunities in traps or in combination with IGISOL techniques and post-acceleration. The latter scheme avoids the drawbacks of an ISOL facility with respect to very short-lived nuclides as well as sensitivity to chemical properties.

Particle tracking and complete particle identification detectors are standard diagnostic elements in an in-flight separator that have to be adapted to the requirements of the next-generation facilities. For example, fast in-flight detector systems and triggered time-projection chambers (TPC) are presently under development. Such TPCs, also under development for CERN’s ALICE experiment, will only trace particles in coincidence with events registered in selected detectors at other focal planes. RICH detectors for velocity determination can be advantageously placed after the separation stage at low count-rates, in this way the start detector for time-of-flight (TOF) is not required. Several prototype detectors have already been successfully tested at the FRS.

### 5.3 Experimental Tools

The challenge of the new generation of experiments with relativistic exotic nuclear beams of unstable nuclei is the possibility of investigating the structure of the nucleus in all its aspects, combining decay studies with the various tools of reaction studies. Possible topics include:

- exploring the limits of stability and the neighbouring regions beyond stability;
- obtaining better statistics and resolution and performing high-resolution experiments;
- providing systematic experimental data for complete chains of isotopes for a fixed element which permit stringent tests of theoretical models to be made;
- and developing new experimental techniques for exploring new nuclear properties not accessible for unstable nuclei, for example continuum spectroscopy.

The following experimental techniques for structure investigation will be discussed in more detail.
- Decay and in-beam spectroscopy to investigate basic nuclear properties such as half-lives down to $10^{-13}$ s, decay Q-values, low lying excitations and high-spin levels, for which we can extract shell structures and deformations.

- Nuclear reaction studies in the limiting fragmentation regime including absorption measurements, elastic and inelastic scattering, stripping, knock-out, break-up in complete kinematics, exploration of interaction radii, matter distributions, and single-particle structure including near and beyond dripline spectroscopy as well as cluster formation and fission.

- The new class of precision experiments in heavy-ion cooler-rings such as precision mass spectrometry, isotope shifts, hyperfine spectroscopy and nuclear decay of bare or few-electron ions to inspect the nuclear surface for shell strength, regions of deformation to learn about electron capture and internal conversion and to selectively study rare decay channels.

- Reaction studies in cooler rings, unexplored up to now, with internal targets (complementary to the reaction studies discussed above, but with better precision) and in ion-electron (A,e) colliders. Electron-ion scattering yields information on nuclear charge distributions, giant resonances and magnetic excitations at well defined energy and momentum transfer. Clear advantages compared to conventional experiments are the large recoil energies of the heavy reaction-products, which therefore can be identified unambiguously, and the use of thin targets and bare nuclei resulting in clean experimental conditions free from atomic deterioration effects such as energy loss, angular scattering and interaction with the electrons of the probed atomic nucleus (Moeller-scattering), which normally leads to large backgrounds. It should be noted here that such experimental conditions would also lead to new data of unique quality and precision for stable nuclei.

As an example of the complementarity of the techniques, the investigation of the nickel isotopes with three doubly magic nuclei at the neutron numbers 20, 28, and 50, and the tin isotopes with doubly magic nuclei with 50 and 126 neutrons is discussed below (see Fig. 5.7).

![Figure 5.7: Production yields of Ni and Sn isotopes from projectile fragmentation (green) and projectile fission of $^{238}$U (red).](image)

For the tin isotopes we find that experiments in the heavy-ion collider need the highest beam intensities. Charge distributions, including the diffuseness of the proton core, can be obtained for intensities of the order of $10^9$/s, specifically for neutron-rich species including $^{132}$Sn and nuclei along the r-process path. Charge radii from electron scattering or laser hyperfine experiments only need intensities of $10^4$/s and can already be measured for about 35 isotopes for one element. Hadronic interactions such as proton scattering in reverse kinematics and GR studies will give access to the nuclear matter distribution and especially the thickness of the neutron skin. Decay studies including gammaspectroscopy and direct mass measurements can be performed at rates below 1/s and can be extended from beyond $^{100}$Sn, close to the proton dripline, towards $^{140}$Sn; regions hitherto completely unexplored.

For the nickel chain, the situation is also very exciting because the experiments can be extended over the full range between the proton dripline and the extreme neutron-rich nuclei $^{78}$Ni. Here the diffuseness can be measured close to $^{78}$Ni and charge and matter radii up
to $^{74}$Ni, close to the doubly magic shell closure. The region around the doubly-magic nuclei $^{48}$Ni and $^{78}$Ni can be explored by decay spectroscopy and direct mass measurement. By combining all methods available in the future, a conclusive picture may be obtained about, for example, the evolution of shell strength towards the neutron and proton driplines as well as the coupling between protons and neutrons from $N = Z$ to extremely unbalanced neutron rich systems where the surface of the proton distribution separates from that of the neutrons. The direct measurement of the diffuseness of the proton skin by electron scattering in combination with detailed spectroscopy gives information on the isovector and spin-orbit forces and the evolution of nuclear shells. With the technique of photon production with electron beams and undulators, relative charge radii could be measured even with rates of 1 atom/s.

In conclusion, the combination of detailed information near stability with the measurement of basic properties towards the most exotic species near the driplines will reveal the structure of nuclei at extreme isospin. Such a strategy has been shown to be extremely successful in fields such as super-heavy element research.

### 5.3.1 Decay studies

The in-flight technique is a sensitive technique for measuring basic nuclear properties such as masses, half-lives and decay energy. Its application to relativistic nuclei has been successful in determining the half-life and providing first information on the $Q_{\beta}$ of $^{100}$Sn on the basis of the observation of seven atoms. The basis of such experiments with few-atoms is high sensitivity, efficient separation and unambiguous identification.

In the regime of relativistic energies, the technique relies on coincidences between the implantation of the in-flight identified nucleus and its decay. To achieve an unambiguous correlation the detectors are position sensitive with high granularity. The position definition allows the decay history of single atoms to be observed and several generations of decay to be followed. For $\beta$-decay, high detection efficiency has also been provided, as demonstrated in the $^{100}$Sn experiment where three decay generations could be followed. Towards the driplines, many decay channels will be opened. The detector must therefore record multi-particle emission.

The ideal detector system should:

- detect all charged particles and provide unambiguous Z-determination of the decay products also for low multiplicity,
- have high granularity to allow for correlation of decay sequences for single-atoms (delayed coincidences),
- detect high-energy $\gamma$-rays of up to 10 MeV with high efficiency, resolution, and granularity,
- and detect neutrons with low detection threshold and short coincidence time because of the possibility of short decay cascades.

For charged particles, detector arrays and stacks of thin Si ($d \leq 300$ mm) position sensitive detectors have been used in the first experiments. Energetic fragments become deeply implanted in the silicon material because of their long range. This automatically guarantees 4π-geometry for the decay products. The position sensitivity of the stack allows the decay particles including betas to be tracked. This has already been successfully applied in the FRS experiment on $^{100}$Sn (see Fig. 5.8). A reliable and high-efficiency detector system is necessary to follow all decay generations without loss in order unambiguously to assign the decay products to mother and daughter generation, for example, for half-life determination on the basis of few atom decays. A still unsolved problem is the detection of low-energy decay particles immediately following the energetic implantation.

A completely new access to gamma-ray spectroscopy has been opened up by the recently developed large-volume gamma arrays with high sensitivity even for large energies up to 10 MeV. Moderate granularity allows low-multiplicity detection and correction to achieve efficient and clean photo-peak detection. Recent decay studies have demonstrated in the example of isomers
that $\gamma$-spectroscopy is already possible with rates of below one atom per second. This opens up a rich field of research beyond the regions of known isotopes, as demonstrated in recent experiments at GANIL and GSI (see Fig. 5.9).

![Gamma-ray spectrum from the K-isomer in $^{190}$W.

Figure 5.9: Measured gamma-ray spectrum from the K-isomer in $^{190}$W.]

Key topics for decay studies are as follows.

- Shell strength far-off stability and the question of shell quenching, and more generally the persistence of shells in the vicinity of magic numbers. Here, the regions near $^{132}$Sn and $^{78}$Ni in particular, but also near $^{208}$Pb are of interest. Careful systematic spectroscopy is required to identify shell quenching, the disappearance of shells due to a transition from mean-field to correlation dynamics, experimentally.

- The extension of shell patterns into the continuum of weakly bound nuclei.

The ideal test case is $^{78}$Ni, which is close to the neutron dripline. Isomer studies in this region will yield information about the high-spin levels close to the Fermi surface, about seniority and about spin-gap isomerism. Feeding rotational bands from K-isomers yields direct information on deformation.

The $\beta$-decay of $^{190}$Sn and its N = Z neighbours is of interest because it will allow the effects of isospin-symmetry breaking to be studied. It is also the best case for probing the quenching of Gamow-Teller transitions in $\beta$-decay. More specifically p–n pairing interactions are studied best in N = Z nuclei up to $^{190}$Sn. Their influence on Fermi decay and E1 transitions can be investigated in this region.

Other examples of experiments are isospin mixing and its relation to Fermi decay and E1 transitions, two-proton decay with the question of correlated proton emission, half-lives, deformations, $P_n$ values along the r-process path and the exploration of r-process nuclei.

Fragment beams of low energy bring their own range of possibilities. Mono-isotopic fragment beams or those with well defined composition can be provided at practically any energy either after slowing down in matter of appropriate thickness or after deceleration in a cooler ring. They can be used for reactions at reduced energy, such as transfer, or for in-beam gamma-spectroscopy. The problem of Doppler broadening is reduced at low energy. While the fragment separator will deliver beams of short-lived isotopes with only moderate longitudinal and transverse emittances, beams from a storage-cooler ring will be of high-quality for nuclides with half-lives in excess of 1 s.
An option currently under development is an ion trap to catch the decelerated fragments in-flight. The theoretical background to tailor the range distribution of the stopped fragments has been developed and experiments for its their verification are under way. Trapped ions could serve as an extremely thin source for precision experiments such as high-resolution mass measurements, conversion electron spectroscopy or beta-neutrino recoil experiments. Re-acceleration could provide low-energy beams for reaction studies at astrophysical energies, at the Coulomb-barrier and in the Fermi domain.

5.3.2 Reaction studies

A major achievement of the new high-energy in-flight facilities is the possibility of probing the structure of exotic nuclei in nuclear reactions and to combine information thus obtained with that from decay studies. A clear case where this has proven to be useful is the example of the halo nucleus $^{11}$Li. In the future, correlation with binding energy and halo size, as well as the level structure and wave functions, could be established and thereby contribute to a consistent picture of the structure of both proton and neutron halo nuclei. The evolution of nuclear structure from light few-body to heavy systems of genuine many-body character accompanied by a transition from clusters to mean-field dynamics might also be investigated [129].

Elastic and inelastic collisions are used to probe nuclear potentials and matter distributions. Exotic nuclear beams could provide a powerful complement to such techniques. Through stripping, knock-out and Coulomb excitation, for example, they may be used to explore the wave functions of valence nucleons by measuring their momentum distribution. An effective method is to use the fragment separator as an energy-loss spectrometer for precise measurements of the momentum distribution after removal of valence nucleons in break-up reactions at high energy. Both neutron and proton halo structures were discovered in such experiments, for example in the nuclei $^{11}$Be, $^{19}$C, $^{8}$B and $^{26}$P. Important additions to momentum measurements are measurements of removal cross-sections and gamma-ray spectroscopy in coincidence with the core. In Fig. 5.10, examples of the momentum distributions of carbon isotopes after 1-neutron removal reactions are shown. On the left, the distributions have been normalized to unity to illustrate the different widths whereas the corresponding distributions on the right panel are weighted by the removal cross-sections. The latter observation demonstrates that enhanced removal cross-sections are clear signatures of halo properties. Removal cross-sections and break-up in selected states deduced from measured gamma-rays in coincidence contribute to an unambiguous interpretation in terms of nuclear structure.

![Figure 5.10: Momentum distributions of $^{11}$C, $^{18}$C and $^{19}$C after one neutron removal at about 900 MeV/u in a carbon break-up target. The distributions have been transformed into the reference frame of the projectile system.](image)

The cases described are single-halo systems and the remaining fragment reflects the internal momentum of the knocked-out nucleon. The wave functions can be obtained by taking into account corrections due to the reaction dynamics and final-state interactions. Reaction studies of nuclei with two and more halo nucleons, such as $^{6}$He, $^{8}$He, $^{11}$Li and $^{12}$Be, require kinematically complete experiments with an analysis of the correlated momenta for all reaction products. In this way the momentum distributions and thus spectroscopic information of particle unstable residual fragments can also be reconstructed. Inelastic scattering, invariant-mass spectroscopy and angular correlation are pow-
erful tools in obtaining the structure and excitation properties of such many-halo nuclei (see Fig. 5.11). The information extracted is the nuclear matter distribution including the evolutions of skins and halos, excitation spectra and multipolarities of the excitation strength, wave functions and nucleon-nucleon interactions and correlations.

- and soft modes and magnetic excitations providing information on the spin-structure of halos, for example.

The in-flight method at relativistic energies with projectile fission has opened up two new fields. The discovery of about 120 extreme neutron-rich fission fragments has already been mentioned. The other new field is low energy fission studies of secondary beams from $^{234}\text{U}$ down to $^{205}\text{Ra}$. In this case, secondary beams were produced by fragmentation, spatially separated in-flight and excited in a secondary lead target. The measured nuclear-charge distributions, shown in Fig. 5.12, directly illustrate the transition from asymmetric to symmetric fission and strong proton odd-even effect in fission yields. Information on nuclear pairing up to higher excitation energies and new aspects of binary and ternary fission for a large number of nuclei that were not accessible by conventional techniques are unique results in this region of nuclides.

Key topics for future studies are:

- the study of the many-body interactions, which cannot be directly extracted from the binary interaction in classical scattering experiments;
- the existence of halos in heavier nuclei;
- multi-nucleon skins and halos;
- the density dependence of the pairing strength;
- changes of spin-orbit potentials in skins and halos;
- giant resonances to study isovector force and extract global properties, for example the polarizability of asymmetric nuclear matter;

Figure 5.12: Measured fission charge distributions of secondary beams excited in a lead target. The secondary beams were produced by fragmentation of 1 GeV/u $^{238}\text{U}$ ions.

In addition, the following are also key topics for further fission studies:

- shell effects at extreme deformation and their temperature dependence,
- and pair breaking.

Comprehensive studies of nuclear structure and reactions, as outlined above, require the full energy range from 50 MeV/u to 1 GeV/u. This demands a network of in-flight facilities on the national and international level to provide optimum research conditions in Europe. GANIL,
the U 400M project at Dubna and GSI would cover the full energy range. While at the low-energy facilities there is a close instrumental overlap with ISOL facilities, the experimental challenge for the next-generation reaction experiments is in the high-energy and heavy-element region.

Reaction studies in the high-energy regime have several advantages. The use of thick interaction targets of the order of $10^{23}$ atoms/cm$^2$ yields high luminosities even for weak fragment beams. Basic properties such as radii or breakup momentum distributions can be measured with intensities of below 1 atom per second and are thus available even for the most exotic species, as outlined above. Scattering experiments, by way of comparison, down to the first minimum at 1 mb need rates of the order of 1000/s.

Another advantage of high energies is that in the laboratory system all reaction products, including breakup neutrons and fission fragments, are emitted in the forward direction into a cone of about 100 mrad. This means that only moderately sized forward detector systems are required to achieve $4\pi$-geometry for full exploration of the reaction phase space. The set-up should be able to measure all reaction products in complete kinematics with sufficient resolution for the mass-identification of heavy nuclei such as fission fragments. Gamma radiation may be used to include nuclear excitation in the reaction analysis. The physical value of correlation measurements between all particles emitted in covering essentially the full phase-space is superior to conventional methods, even with low statistics.

The technical requirements for a next-generation set-up are:

- a fast projectile event-by-event identification for mixed-beam experiments and complete tracking of hot fragments,
- a liquid-proton (deuteron, helium) target,
- a target calorimeter or high-resolution $4\pi$-gamma tracking array with high granularities for in-beam spectroscopy,
- a large-gap dipole magnet or a large acceptance spectrometer,
- charged particle detectors with mass, position, and velocity measurement of high resolution at moderate multiplicity,
- and efficient position sensitive neutron detectors for low multiplicity neutrons.

An example of the next generation set-up for reaction studies is shown in Fig. 5.13.

![Figure 5.13: Set-up for reaction studies in complete kinematics.](image-url)

Design studies for such a set-up are the subject of an RTD proposal R3D approved by the 5th Framework Program of the EU. The secondary beams for the reaction studies are provided either directly from the fragment separator or with best beam quality from the cooler ring. The set of targets should include liquid hydrogen targets suitably shaped for the detection of protons scattered under large angles and of well-defined thickness for cross-section measurements for incineration studies, for example.

The target calorimeter can be a close-geometry scintillator. For in-beam spectroscopy an optimized combination of high granularity and high resolution germanium arrays and NaI detectors are under discussion.

The high fragment velocity allows precise velocity determination using RICH detector systems. Typical resolution is $\Delta \beta/\beta = 10^{-3}$. For particle tracking and charge identification at high rates, a large number of detectors is in use. Advanced solutions are scintillating fibres and, for heavier nuclei, silicon-strip arrays and large area neutron detectors.
The key instrument of the set-up is the magnetic spectrometer. Two types of spectrometers are under discussion. Firstly a large-gap dipole with sufficient field integral to provide the required resolution in combination with the tracking system (a mass resolution of about 200 for fission fragments, for example), which would be part of a system for break-up studies in complete kinematics. And secondly a focusing large-acceptance superconducting energy-loss spectrometer for high resolution. A high-resolution spectrometer could also be used with cooled fragment beams. It would be used in forward peaked reactions for precise momentum distributions and spectroscopy from knock-on reaction and Coulomb excitation.

Such universal instrumentation would allow a rich variety of experiments. Of special interest, however, are the light nuclear systems which can be treated with high accuracy by many-body interactions. Such systems should be explored in complete kinematics from the proton to the neutron driplines with highest possible precision including break-up reactions and elastic and inelastic scattering. Questions to address are multi-nucleon interactions, cluster phenomena, the shielding of the continuum by the Coulomb barrier and the pairing and continuum interactions on the neutron-rich side reflecting behaviour at the limit of unbound matter.

The evolution of nuclear structure and the development of the mean field towards heavier systems is of fundamental interest as it represents the lowest level of complexity in our world. The investigation of isotopic chains of selected elements from the proton dripline to the neutron dripline will be possible up to nickel. Besides the level structure the growth of the neutron skin and the possible interplay with shell structure in such a heavy system would also be of interest.

Electromagnetic excitation is a powerful tool for exploring the level structure and determining lifetimes. Gamma-ray spectroscopy in coincidence with the implanted isotopes at several hundred MeV/n represents a rich source of information of high sensitivity.

A study of the giant resonance in asymmetric nuclear matter and the direct measurement of the neutron skin by observation of the GMR would complete our knowledge on exotic nuclear matter.

Fission studies of the unstable actinides have already brought interesting results on the charge distribution of the fission fragments. Still unexplored, however, is the mass distribution. Moreover a well defined temperature definition of the fissioning system by measurement of the neutron multiplicity would be of importance to contribute to the still not well understood shell survival at moderate nuclear excitation. This problem is not only relevant for the study of fission dynamics but crucial for the production of super-heavy elements.

Precise measurements of n and p induced spallation cross-sections and neutron multiplicity could be achieved by experiments in inverse kinematics on proton and deuteron targets. This information is needed for nuclear waste burning and the design of spallation neutron sources. Such measurements are of interest for all materials used in the converter and reactor such as uranium, bismuth, lead, or iron and over large energy ranges up to 1 GeV.

With the exciting new information obtained from satellite observations there is strong interest in a better understanding of nucleosynthesis. A contribution to nuclear astrophysics from in-flight facilities can be the study of capture reactions in reverse kinematics. For example, instead of investigating directly the \( (p,\gamma) \) reaction characterized by extremely low cross-sections at the astrophysically relevant energy range of keV, Coulomb dissociation \( (\gamma,p) \) with radio-active projectiles can be successfully applied. This method, studied in the \( ^8\text{B}(\gamma,p)^7\text{Be} \) reaction at high energies, has a significant advantage compared with similar studies at other facilities at intermediate energy because higher-order effects are strongly reduced. This makes the interpretation of the data unambiguous. The higher intensities of a next generation facility would allow experiments to contribute to the important topics in the rp-process.
5.3.3 Precision experiments with stored and cooled beams

Ion cooler rings have been used at Coulomb-barrier energies (TSR, Heidelberg) as well as at relativistic energies (COSY, Jülich and ESR, Darmstadt). Storage rings are complementary to ion traps, however, with the capability of accepting in-flight separated ions with large phase-space at full energy. The application of storage rings to heavy-ion physics opens up a completely new field of precision experiments including the study of ground-state properties, nuclear dynamics and the interaction of the nucleus with its cloud of atomic electrons [125, 130].

Highlights in the field of unstable nuclei are the discovery of the $\beta$-decay of fully stripped ions into unoccupied bound electron states for $^{163}$Dy and $^{187}$Re and the mapping of the mass surface along the neutron-deficient isotopes with an accuracy of about 100 keV. The mass measurements have been performed by Schottky Mass Spectroscopy (SMS) in the storage ring ESR. SMS is based on electron cooling to force all the circulating ions to an identical mean velocity with a spread below $10^{-6}$. Access to short-lived nuclei is currently limited, by the cooling time and the time needed for Schottky spectroscopy, to nuclei with half-lives longer than about 10 s. Experimental results are compared with different theoretical models in Fig. 5.14. Systematic studies over large mass ranges are especially valuable for improving nuclear models and for effective force parametrization.

A novel method has recently been introduced whereby the revolution time of the stored fragments is measured without applying electron cooling. The ESR is operated in isochronous mode whereby all particles with identical mass-to-charge ratios have the same revolution time independent of their velocity spread. The power and potential of this Isochronous Mass Spectrometry (IMS) has been clearly demonstrated. A precision of about $5 \times 10^{-6}$ for many nuclei has been achieved and new masses down to millisecond half-lives have been measured, some examples being $^{44}$V, $^{43}$V and $^{41}$Ti. The main advantage of IMS is that practically all ions with half-lives longer than the flight path from the production target can be measured. This opens up the possibility of half-life measurements down to the microsecond range.

Key topics for further studies in this area are:

- the exploration of the nuclear mass surface near shell closures, driplines, and the astrophysical paths of nucleosynthesis,
- the study of $\beta$-decay of bare or few electron ions,
- hyperfine structure and isotope shifts,
- and nuclear reactions of highest precision at the internal target.

For optimum performance, a storage ring system should consist of a dedicated collector ring and a separate storage ring dedicated to the experiments. To inject projectile and fission fragments covering a large phase space efficiently, optimum matching of the separator emittance and the collector acceptance is required. In addition, phase-space compression with ion-optical methods, as discussed above, or bunch-rotation techniques can be applied. These problems are not yet solved and need further ion-optical studies and test experiments.

The collector ring, with a large acceptance to efficiently collect the projectile fragments, should include fast cooling with times below 0.1 s and the capability of deceleration or acceleration for injection into the experimental ring.
with an energy appropriate for experiments. Because of their large momentum spread, the combination of stochastic and electron cooling is most promising for projectile fragments. Figure 5.15 shows the emittances and the momentum spreads of cooled gold ions. These parameters strongly depend on the number of stored ions. It should be noted that the momentum spread decreases to $\Delta p/p < 10^{-6}$ for numbers of stored ions below 1000.

![Figure 5.15: Emittances and momentum spread of cooled gold ions in the storage ring ESR.](image)

Experiments with cooled beams of exotic nuclei interacting with the internal gas target will open a new field in terms of physics and experimental techniques. Scattering experiments with cooled exotic beams will be characterized by high precision. Atomic energy loss and scattering in targets with densities of $10^{13} - 10^{14}$ atoms/cm$^2$ are compensated by the cooling force. The luminosity for $10^7$ fragments circulating in the ring, taking into account the circulation frequency of $10^6$/s, corresponds to $10^{27}$/cm$^{-2}$ s$^{-1}$. In other words, one can expect an event rate of 1/s for a cross-section of 1 mb. Experiments like $(p,p')$ and $(\alpha,\alpha')$ will be performed in reverse kinematics with hydrogen or helium gas-jet targets. Coincidences between the scattered target nuclei and the fragments will allow extremely clean, background-free experimental conditions.

The necessary technical developments include:

- resonant pickups to detect low-intensity beams down to single ions;
- development of gas-jet and cluster targets with densities larger than $10^{14}$ cm$^{-2}$;
• particle detectors including Z-definition to register particles from nuclear decay or reaction products leaving the closed storage orbit;
• and 4π-set ups for reaction studies with tracking capability to determine the scattering angles in complete kinematics with mass and charge determination of heavy ions including fission fragments, light charged particles, neutrons and γ-rays.

The question of to what extent ring components such as the large dipoles could serve for high resolution momentum analysis needs further investigation.

Key experiments are as follows.

• Direct mass measurements to explore the nuclear binding energies of the light halo nuclei, mapping of the mass surface and shell strength near $^{106}$Sn, $^{78}$Ni and $^{208}$Pb, and, in the regions of the rp- and r-process, precise mass determination of near N = Z nuclei to learn about the pn interaction. Precise Q$_{3}$-values and half-lives that could be measured would contribute to the unitarity test of the CKM matrix.

• High-resolution collinear laser spectroscopy to measure hyperfine structure and isotope shifts to access nuclear moments and charge radii. The implication of the new generation of power lasers to improve sensitivity must be investigated further. Photon sources of high energy around 100 keV would allow spectroscopy of hydrogen or lithium like systems where the highest precision could be achieved. A challenge would be single-atom spectroscopy which may become possible with SASE free electron lasers. Laser spectroscopy of Li-like heavy ions will be possible with, for example, the high-power laser system of GSI as a pump source of an X-ray laser. During the few-picosecond duration of the X-ray pulse, corresponding to nearly one Megawatt of laser power, the saturation requirements of an allowed 2s-2p transition in a Li-like heavy ion of about 200 eV transition energy are closely matched.

• Elastic proton scattering in reverse kinematics, discussed in the previous section, could be performed under ‘thin-target conditions’. Inelastic scattering (p,p'), (α, α') and charge exchange (p,n) reactions represent well established methods for studying nuclear multipole response. (p,n) and (p,p') reactions near 0° and at energies of approximately of 0.2 GeV/u to 0.4 GeV/u are an excellent tool for studying Gamow-Teller (GT) transitions. Detailed knowledge of GT strength in fp shell nuclei in particular plays a key role in understanding the core collapse of massive stars that triggers Supernova explosions. With the (α, α') reaction studies of Giant Monopole Resonances can be performed to extract the compressibility of weakly bound exotic nuclei [131, 132]. Isovector excitations in particular are considered to be sensitive to the thickness of the neutron skin. Coulomb excitation in heavy gas targets could be used to investigate the inverse capture reaction, already discussed as relevant for cosmic nucleosynthesis. Thin targets would help to provide precise data down to low proton energies.

5.3.4 Structure studies with colliding beams: electron scattering from exotic nuclides

Electron scattering from unstable nuclei would considerably extend our knowledge of the nucleus and contribute to a conclusive picture of nuclear structure [133]. A first technical proposal for a low-energy electron–heavy-ion collider has been made at Dubna in the framework of the K4-K10 project. The idea has been further developed and discussed at GSI and is part of an extension of the physics programme there. An electron–heavy-ion collider is also part of the new MUSES facility at RIKEN [133]. For structure research and for the investigation of nucleon momenta, electron energies ranging from 100 MeV to 800 MeV (c.m.) are needed. With these energies electroproduction of pions in unstable nuclei may also be studied.

Electron–ion collider experiments have the following advantages in comparison to conventional fixed-target experiments.
- Experiments with unstable nuclides.
- The large recoil energy allows an unambiguous identification of the heavy reaction products which is of importance, for example, in electro-fission.
- Forward kinematics of the relativistic heavy ions permit measurements of coincidences between the scattered electrons and the heavy recoils in a nearly $4\pi$ geometry. The background resulting from the radiation tail of elastically scattered electrons is thus completely suppressed.
- The stored ions are bare, which means that the large background from scattering with bound electrons is absent.

The clean, backgrounds free spectra will provide a much higher sensitivity than in conventional experiments. Electron scattering does however, present an experimental challenge requiring a number of new developments:

- physics of interacting cooled beams with high luminosity,
- experimental techniques with colliding bunches - a new field for structure research,
- and the development of high resolving-power large-acceptance electron spectrometers with tracking capability for scattered electrons to achieve precise momentum and angle determination.

Electron scattering will open up a completely new field of physics of exotic nuclei with an enormous discovery potential. Examples for experiments are listed below.

- Elastic scattering is an established tool to measure root mean square charge radii and charge diffusenesses. New experiments of this type would help to determine the proton and neutron skins. Knowledge of diffuseness will contribute to the exploration of the neutron-proton interaction, of whether the charge surface becomes diluted in the neutron skin and of the interplay of the diffuseness with the spin-orbit force. For example,

Fig. 5.17 shows the calculated form factor of different tin isotopes. Radii can be obtained by exploring the region around the first maximum, the required luminosity for this is $10^{23}$ cm$^{-2}$s$^{-1}$. The diffuseness can be obtained from the second maximum with a luminosity of $10^{27}$ cm$^{-2}$s$^{-1}$. These luminosities hold for a 1 Hz event rate.

- Inelastic scattering is an excellent probe for bound and unbound low spin states.
- Excitation of electric and magnetic giant resonance gives access to collective phenomena and the nuclear equation of state near zero temperature.
- Electro-fission could be studied under well defined momentum and energy transfer and over a large energy range in $4\pi$-geometry.
- Electron induced dissociation as inverse capture or for extracting cross-sections of neutrino induced reactions for astrophysical applications.
- The measurement of nucleon momentum distributions of specific interest for weakly bound systems such as skin- and halo nuclei.
- In-medium effects.

![Figure 5.17: Calculated charge form-factors for different tin isotopes.](image-url)
Additional options are the production of intense radiation by undulators, synchrotron and channelling radiation for research and application, photon-electron and photon-ion scattering and storage of protons and deuterons in the electron ring for hadronic collisions with exotic nuclei.

The electron synchrotron and storage ring would be connected to an appropriate heavy-ion cooler ring and could be operated in colliding (co-propagating) or merging (contra-propagating) modes. Luminosity is limited by the emittances of the ion beam (space charge and cooling). The advantage of the merging mode is higher luminosity and strongly forward peaked kinematics. In the colliding mode the centre-of-mass energy is considerably increased.

The electron synchrotron and storage ring complex is of moderate size, circumference being about 20 m. Electrons would be provided by a 100 MeV high current superconducting linac (10 mA) which can be used for the production of highly intense mono-energetic photon beams (up to $10^{10}$ photons/s) at times when the ring is not loaded. With undulators and channelling radiation, mono-energetic photons could be provided in an energy range from eV to several 10 keV. Multi-turn injection would fill the ring to its capacity of $3 \times 10^{11}$ electrons. The stored electrons could then be accelerated to a maximum energy of 400 MeV. Currently $10^4$ ions stored in the ring provide a luminosity of $10^{25}$ cm$^{-2}$s$^{-1}$, sufficient for the determination of charge radii. This luminosity is equivalent to that of hadronic scattering at an internal proton target of $10^{12}$ atoms/cm$^2$. Both methods can therefore be combined in one experiment. Together with a 10 Tm ion storage ring, centre of mass energies of 40 MeV to 800 MeV (co- and contra-propagating beams) can be obtained.

The reaction kinematics for the scattered electrons and the recoiling nuclei need detailed investigation. This is an interesting problem because the technique of colliding beam bunches is new to the field of nuclear structure. A large acceptance electron spectrometer of high resolution must be developed. This should have a solid angle of greater than 100 msr, momentum acceptance $\Delta p/p > \pm 10$ and energy resolution $\Delta E/E < 5 \cdot 10^{-4}$.

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<th>Table 5.2: Parameters for the collider</th>
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<td>Circumference</td>
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<td>Maximum energy</td>
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Conditions for the heavy-ion ring

| Parameter                             | Value         |
|---------------------------------------|
| Ion energy                            | 300 MeV/u     |
| Ions per bunch (space-charge limited) | $10^8$ uranium 92+ |
| No. of bunches                        | 10            |

Key experiments include the measurement of charge radii and diffuseness of magic nuclei, for example $^{56}$Ni and $^{132}$Sn. Systematic studies of the isotopic chains of skin and halo nuclei allowing the exploration of proton skins are another area of interest. Core compression could also be investigated, as well as the correlation of the diffuseness of the proton surface to the thickness of the neutron skin, its influence on the spin-orbit force, and the level structure.

In principle, all experiments involving Coulomb excitation can be performed with inelastic electron scattering under much cleaner conditions than in hadron scattering. In the Coulomb process on heavy targets, a burst of equivalent photons interacts with the nucleus. The electron scattering is a one photon exchange interaction with well determined energy and momentum transfer. Inelastic scattering for spectroscopy of bound and unbound low-spin states allows transition densities from form factors to be accurately obtained since multi-step excitation is suppressed. Variation of momentum transfer allows the selected excitation of different multipoles. As the cross-section for the exci-
tation of giant resonances is of the order of some 10 mb, strongly dependent on the scattering angle, luminosities of $10^{28}$ cm$^{-2}$s$^{-1}$ are required.

Quasi-elastic scattering at large momentum transfers allows binding energies and nucleon momentum distributions to be determined. These can be derived from the position and width of the quasi-elastic peak respectively. The luminosity necessary for such experiments is $10^{30}$ cm$^{-2}$s$^{-1}$.

Electron scattering can contribute to the understanding of neutrino nucleosynthesis since electron cross-sections can be transformed to neutrino cross-sections. An example is the reaction $^{12}\text{C}(\nu, \nu')^{12}\text{C}*$ and the branching of the excited atom's decay into $^9\text{Be} + ^3\text{H}$, $^{10}\text{B} + d$ and $^{11}\text{B} + p$. In colliding beam experiments, contrary to conventional experiments, the decay particles are produced with high recoil energies. Branching ratios can easily be measured in 4$\pi$ near the particle thresholds. This might contribute to solving the long standing problem of the production of the light elements $^9\text{Be}$ and $^{10,11}\text{B}$ which can be neither synthesized in the Big Bang nor in stellar hadronic reactions [134].

An interesting option with an intense electron beam is high-intensity photon beam production by means of undulators, FELs, and of synchrotron radiation, which will have a broad field of applications. Interesting physics from photon collisions with ions having only few electrons includes the investigation of isotope shifts and hyperfine structure to determine spins and nuclear magnetic moments.

With an electron injector delivering short pulses in combination with peta-watt lasers, photon-electron scattering would deliver intense laser-like X-ray bursts for nuclear studies, a new and extremely interesting field of physics the discussion of which just has started.

5.4 Conclusions and Experimental Developments

In conclusion, the next generation in-flight facility will not only extend our present ability to proceed further towards the limits of stability, approaching the neutron dripline to elements as heavy as nickel, but will also open up new access to nuclear structure studies by introducing new experimental methods. Nuclear reactions in storage rings and in an electron–heavy-ion collider will play a key role in the future.

The high complementarity of ISOL and of fragmentation at intermediate energies should always be considered in experimental development and in the physics programme as well.

Challenges not discussed in this paper, but recommended for investigation are the use of driver accelerators and storage-ring systems for interdisciplinary research and applications such as atomic and solid-state physics, biology, medicine and the problem of world energy supply for coming generations.

Experimental developments as recommended in the November and December '98 meetings of the working groups are summarized below.

Accelerator techniques:

- the development of ion sources for rare isotopes and high current injectors involving new techniques such as funnelling to improve the intensities of not space-charge limited light beams;
- the development of synchrotrons for intense beams of heavy elements, specifically uranium, including new techniques such as high temperature superconducting magnets;
- the development of accumulator rings with large acceptance and fast cooling involving stochastic cooling and electron cooling to access cooling times of 0.1 s.

Separators:

- large acceptance high-resolution fragment separators with high background suppression including superconducting large-acceptance quadrupole magnets for beams of up to 18 Tm magnetic rigidity;
- dispersive stages for energy bunching and slowing down in gas cells;
• tracking and particle identification detectors for high count rates.

Experimental equipment.

For decay studies:

• implantation detector arrays of high granularity,
• and $4\pi$ gamma and neutron arrays.

For break-up studies:

• magnetic analysers of high resolution for reaction studies,
• and $4\pi$ gamma arrays of high granularity to correct for Doppler broadening.

For storage ring and e-A collider experiments:

• gas targets of high density $10^{14}$ atoms/cm$^2$,
• detection systems for scattering experiments including particle detectors for scattered target and beam nuclei,
• large acceptance electron spectrometers including a detector system with tracking capability,
• luminosities achievable with ultra-cold ion beams.

To collect the best possible expertise these developments should not be limited to the European community but be made in world-wide collaborations in close contact with laboratories planning or running in-flight facilities and the ISOL community.

The use of the new generation of light sources, such as intense lasers of the new generation and SASE - FEL, should be investigated.
6. Conclusions

In this concluding chapter, we examine to what extent the terms of reference given by NuPECC to the Working Group have so far been accomplished. We present the recommendations that our work to-date allows us to make, and we reiterate the outstanding problems, discussed at length in the preceding chapters, that remain to be tackled.

Chapter 2 has extensively treated the physics case for Radioactive Nuclear Beams. Similar surveys of the scientific challenges, which are and will be tackled by RNBs, have been carried out before, in Europe and elsewhere, as shown in Refs. [1], [135]–[139]. There is clearly a very large field in nuclear physics, nuclear astrophysics and fundamental interactions which will be covered by the next-generation RNB facilities, both ISOL and in-flight, as also illustrated by some specific examples in Chapters 4 and 5. The next stage will be to propose in detail key experiments and their technical requirements (RNB type, energy and intensity) for the next-generation RNB facilities. In the case of the ISOL method, this will be the first task of the EURISOL project. A similar investigation for the in-flight method is being carried out within the R3B project.

An extensive comparison of the different production methods for radioactive nuclei is presented in Chapter 4, together with a thorough investigation of the technical challenges of the target-ion source assembly in which these nuclei will be produced, extracted and ionized in an ISOL/RNB facility. The choice between the various possible options will be dictated by the physics requirements identified by the ongoing RTD projects EURISOL and R3B, and also by the possible synergies between a next-generation European ISOL/RNB facility and other major European infrastructures and projects that could share a common driver accelerator. The latter are:

- existing or planned infrastructures in major European nuclear physics laboratories;
- the various beams presently produced for particle physics at CERN or those envisaged for neutrino beams or muon colliders;
- the 800-MeV 200-μA proton beam presently available (mainly) for material studies at the Rutherford Appleton Laboratory in the United Kingdom;
- the proton beam for the envisaged European Spallation Source (ESS) with proposed 1.334 GeV energy and 5 MW average beam power;
- the Accelerator Driven Systems (ADS) envisaged for nuclear waste incineration, with proton beam energies in the 1 GeV range and intensities of several tens of mA.

An extensive investigation of these possible options and synergies is the second task of the EURISOL project. The third task of EURISOL will be to use the results of that investigation, along with the information contained within this report, to draft a conceptual layout of the target-ion source assembly.

The problems related to charge amplification of the radioactive ions, their (isobaric) mass selection and their post-acceleration are treated in Chapter 4, together with some considerations on the recycling of radioactive beams. The common ground with in-flight facilities, storage and cooler rings is treated in Chapter 4. Here also the choice between the various possible options will be dictated by the physics requirements and by possible synergies with existing European
infrastructures. The investigation of these questions is the fourth task of the EURISOL project. Of special interest in this context will be the outcome of the CHARGE BREEDING project, which aims at strong improvements in efficiency for the conversion of \( \text{Li}^+ \) into \( \text{n}^+ \) radioactive ions.

In-flight facilities are extensively treated in Chapter 5. The advantages and limitations of the in-flight method are clearly outlined, as well as its various options, the experimental tools to be developed for decay and reaction studies, and the storage and cooler rings that will be installed to handle the produced beams. Here, a clear recommendation is formulated: the next-generation RNB in-flight facility should accelerate all elements from hydrogen to uranium, to energies up to 1 GeV/u with primary beam intensities of at least \( 2 \times 10^{12} \) ions per sec. In this respect, the R3B project to design and partially implement an advanced experimental set-up for reaction studies with relativistic beams at GSI, Germany, is of special interest.

One point that has not been investigated in detail by the Working Group is the instrumentation to be installed at the planned RNB facilities, although some information is contained in Chapters 4 and 5. For an ISOL/RNB facility, instrumentation will be the EURISOL project’s fifth task. Furthermore, some work in this direction is already under way within various EU contracts. The presently running Concerted Action, ‘Frontiers in Nuclear Physics and Astrophysics (FINA)’ includes one activity on instrumentation at RNB facilities. This will be continued within the extension of FINA ‘Frontiers in Nuclear Physics (FINUPHY)’. The running RTD contract ‘EXOTRAP’ and the new ‘EXOTAG’ project are also of special interest in this regard.

The present status world-wide of RNB facilities existing, at the commissioning stage or being constructed is outlined in a report of the RNB Study Group of the OECD Megascience Forum Working Group on Nuclear Physics which has just appeared [6]. In the United States, the upgrade of the in-flight facility at the MSU laboratory has been funded, and plans for an ambitious next-generation ISOL facility are being drawn-up. In Japan, Phase I of the upgrade of the RIKEN in-flight facility has been funded and Phase II is under consideration. The future of the E-ARENA, an ISOL/RNB facility within the Japanese Hadron Facility, is also under discussion. In Europe, the GSI laboratory is presently the only one in the world that already accelerates intense heavy ion beams up to uranium at energies up to 1 GeV/u to produce RNBS by the in-flight method. Furthermore, GSI is currently investigating in detail a major upgrade of its accelerator complex. This points to a clear need to design a European next-generation ISOL/RNB machine, whose beams are necessary to complement the physics which will be investigated at a European in-flight facility. The EURISOL project aims at a preliminary design study of such a machine, which has the ambition to be the best in the world in order to continue the traditional lead that Europe has enjoyed in the past in RNB physics.

In conclusion, the present report is a first step towards large-scale European initiatives for next-generation RNB facilities. The next step will be to investigate the outstanding problems outlined above within various European projects starting in the year 2000. These include EURISOL, CHARGE BREEDING, R3B, EXOTAG and FINUPHY.
Bibliography


6. Conclusions


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