



HIE-ISOLDE: the scientific opportunities

Editors: K. Riisager, P. Butler, M. Huyse, R. Krücken

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The HIE-ISOLDE project aims at substantial improvements of the energy range, the intensity and the quality of the secondary radioactive beams produced at the ISOLDE facility at CERN. This report presents the questions within nuclear physics and related areas, including nuclear astrophysics, Standard Model tests and condensed matter physics, that scientists will be able to address at HIE-ISOLDE and gives specific examples of how the upgrades will improve the experimental conditions. The physics possibilities at HIE-ISOLDE were reviewed at the NuPAC meeting (Nuclear Physics and Astrophysics at CERN) held at CERN in October 2005; this report gives a more comprehensive overview and incorporates technical and scientific developments that have taken place since then.

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Preface

The present document summarizes the physics motivations for the HIE-ISOLDE project, a major upgrade of the present ISOLDE facility at CERN. Many individuals have contributed directly as well as indirectly to outlining the new physics possibilities that mainly, but not exclusively, fall within the field of nuclear structure.

Owing to their specific building blocks and interactions, atomic nuclei can exhibit many different sometimes mutually exclusive degrees of freedom; e.g. single particle behaviour as a result of shell effects or collective phenomena resulting in part from strong correlations. Both depend strongly on the specific number of protons and/or neutrons and differ from what is observed in stable nuclei. Current model descriptions are tailored to stable nuclei and often fail to predict the properties of exotic nuclei. This is not simply due to a wrong set of parameters used, but is of a more fundamental nature. Efforts based on effective field theories, motivated by the basic symmetries of QCD, to deduce nucleon–nucleon forces for the description of the low-energy nuclear structure of light nuclei are currently under way. The results of this work subsequently find their way into the different approaches used to describe heavier nuclei, like mean field theories, symmetry based interpretation, and shell-model descriptions. Information on the different observables of exotic nuclei with unusual proton-neutron ratios will be anchor points to guide and test these new calculations and will lead to more reliable extrapolations towards unknown territory on the chart of nuclei and, more importantly, to a more fundamental insight into the properties of the strong interaction acting in the nuclear medium. To deduce the essential degrees of freedom and the corresponding eigen-frequencies with which the nuclear many-body systems resonate, external fields, like electromagnetic, weak and/or strong probes, have been used in the past and are now being adapted to radioactive beam experiments. The HIE-ISOLDE project will substantially increase our capability to proceed further due to the widening spectrum of exotic nuclei produced, their availability at different energies, and the use of new instrumentation, in this way matching the innovative theoretical developments.

Karsten Riisager

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1 HIE ISOLDE – The scientific opportunities

1.1 Introduction

During recent decades nuclear physics has become increasingly concentrated around large national and international laboratories. The trend is seen particularly strongly in nuclear structure physics and related areas, where physics studies employing radioactive beams have led to a major reorientation of the field. This development is to a large extent driven by the continuous technical developments and is far from being concluded. CERN has played a special role in this process by hosting the ISOLDE facility for close to 40 years. Although the basic physics principles in the production of radioactive isotopes at ISOLDE have remained unchanged during all these years, a long series of transformations and upgrades have resulted today in a facility that has nothing in common with the first installation and has vastly superior properties. The present ISOLDE facility was commissioned in 1992 and has been expanded several times, the latest addition being the REX-ISOLDE post-accelerator that started operating in 2001. What is proposed now is a major upgrade of the present facility that takes advantage of the latest developments and increases significantly its scope, thereby ensuring that the expertise present at and around CERN will continue playing an important role in the progress in nuclear physics and related fields.

This section will present the general physics motivation for continued research employing radioactive beams. The motivation is not unique to the present HIE-ISOLDE proposal, it has been put forward in several reports during the last decade and the discussion here can therefore be brief. The following sections will give more concrete examples of the new physics possibilities that will appear with HIE-ISOLDE. They do not exhaust the possibilities, but give examples that come from different branches of the present physics programme and together illustrate the broadness of the science scope of the upgraded facility. An extensive overview of the future physics possibilities at HIE-ISOLDE was given at the NuPAC meeting (Nuclear Physics and Astrophysics at CERN) held at CERN from 10 to 12 October 2005. Based on this meeting the INTC gave a very positive assessment of the proposal [NuPAC].

General overviews of the field of nuclear physics have been given by NuPECC [LRP04], OECD [OECD99] and NSAC [NSAC02], in all three cases recommending the construction of next-generation radioactive beam facilities. Two different ways of producing radioactive beams [RBF00], in-flight separation and the ISOL approach, can be combined with different post-processing of the radioactive nuclei. In Europe, the recommendation is to construct separate facilities built on these two complementary production schemes [LRP04, RCI05]. Immediate priority is given to the in-flight project FAIR [FAIR], where construction will start in 2007 and first experiments are planned for 2012. Highest priority for further projects is given to the next-generation ISOL facility EURISOL [EurRep], which can be constructed in the next decade. Currently an intense R&D programme is being carried out [EURIS] to bridge the technological gap between present day facilities and EURISOL. It is recognized that one needs to proceed via several intermediate stage projects, one of them being HIE-ISOLDE and others including SPIRAL2 at GANIL [SPIR2]. Outside Europe several projects also exist. Funding is already secured for the upgrade of the RI Beam Science Laboratory at RIKEN [RIBF] and for ISAC2 at TRIUMF [ISAC2], and in the USA a large community around the RIA project [RIA] is working towards construction of a new facility. Although healthy competition exists between these projects, the long tradition for international collaboration within nuclear physics gives synergy also across continents.

1.2 *The goals of nuclear physics*

Testing the basic theory of strong interactions, QCD, is a major undertaking that involves nuclear as well as particle physicists, however, nuclear physics reaches beyond that. We normally meet strongly interacting matter in the shape of atomic nuclei, built out of quarks that are ‘frozen’ into nucleons (protons and neutrons). There are typically many nucleons, up to 300, in a nucleus so that many different quantum states can be constructed and a rich variety of phenomena appears. It is the task of nuclear structure physics to unravel this myriad of quantum structure and to find the ordering principles that hold in nuclei.

The linking of QCD to the structure of the nucleus is best done in steps. The first steps lead from the basic equations of QCD through effective field theories to nucleon–nucleon forces that can now be used for calculations of nuclei consisting of up to about ten nucleons. For heavier systems our present calculational power is insufficient and one must turn to shell models or mean field models based on effective interactions. Having said this, although the conceptual links all the way back to QCD of course are vital and are needed for a proper founding of nuclear science, the key point in our descriptions of intermediate and heavy nuclei is not necessarily the connection to nucleon–nucleon forces but rather the identification of the important degrees of freedom in the nuclei. Nuclei are mesoscopic systems with two distinct types of fermions where both collective and single particle behaviour are important and where the correlations going beyond a mean field description add significantly to the richness of the phenomenology. The recent revitalization of the field of nuclear structure is due to our ability to do detailed experiments also with short-lived nuclei. Early studies were confined to the essentially one-dimensional selection of nuclei (with the mass as the only ‘changeable parameter’) that are either stable or long-lived. Going beyond these roughly 300 nuclei towards a two-dimensional picture where both proton and neutron numbers can vary over a wide range has already given many surprises. We have still only produced and identified less than half of the possibly more than 6000 different nuclei that can exist, the large remaining *terra incognita* being the very neutron-rich nuclei. One significant remaining challenge is the prediction of the properties of almost pure neutron matter, needed for the description of neutron stars.

For proton-rich nuclei, the progress towards more and more short-lived nuclei has in many cases taken us to the limit of the bound nuclei, the proton dripline. The corresponding neutron dripline lies further away from the stable nuclei and has only been reached up to the neutron number N just above 20. For the extreme systems close to the driplines the theoretical description has undergone a qualitative change, the basic framework shifting from closed to open quantum many-body systems. Development of an intertwined nuclear structure and nuclear reaction theory has also turned out to be needed for a proper explanation of the experimental data. Seen clearly in these regions of the nuclear chart, but suspected to be a widespread phenomenon, are displacements of the energy of the single-particle levels to an extent such that the magic numbers change. This, of course, prompts a rethinking of our traditional understanding of nuclear structure.

The study of radioactive beams allows us to follow the evolution of nuclear structure over extended regions in the nuclear chart, be it the evolution of single-particle energies, that of nuclear shapes, or whatever aspect on which one focuses. Some aspects of nuclear behaviour are seen more clearly in nuclei away from the stable ones. This applies in particular to nuclei that are close to the dripline and therefore close to being unbound, where correlation terms that are small and therefore unimportant in well bound nuclei can have a determining

influence on the structure by giving that last small amount of binding energy that secures binding of the nucleus as a whole. The fact that there are so many more radioactive nuclei than stable nuclei of course also contributes to explaining why it becomes easier to disentangle and isolate different trends in structure evolution. Exotic nuclei with extreme isospin values (neutron–proton asymmetries) will eventually provide stringent constraints on the microscopic description of nuclear structure as well as nuclear dynamics. Adjacent science fields that also employ nuclei, e.g., precision studies of weak interactions or condensed matter physics, will also benefit from having an enlarged range of radioactive nuclei available.

1.3 Experimental probes of nuclear structure

A wide range of experimental techniques are available for extracting nuclear structure information, see, for example, [EurRep, LRP04, RBF00]. Only a brief overview will be given here, more detailed examples are given in later sections.

Starting with the lowest energies, modern day atom and ion traps have, in principle, reached single-atom sensitivity. They are very useful tools both for precision spectroscopy and for beam handling and are already heavily used at ISOLDE which has the highest concentration of traps among radioactive beam facilities. They will be essential components of the upgrade to improve the beam quality and most experiments will benefit from this. An obvious example is the mass measurements in the Penning trap mass spectrometer ISOLTRAP that continuously refines our understanding of the nuclear mass surface.

The improvement in beam quality, the increase in intensity and the availability of new radioactive beams will also boost decay experiments. The half-life and main decay modes of a nucleus belong to its basic properties and where intensities and beam purity allow for more detailed studies one can gain information about many different nuclear structure questions as well as the low-energy behaviour of the weak interaction. To fully characterize a nuclear state, measurements of its size and its electromagnetic moments are also required. Again, ISOLDE hosts several long-running experiments that have successfully contributed to such measurements in the past and all will benefit from the general improvements. Furthermore, new possibilities emerge with tilted-foil polarization using the accelerated beams at REX-ISOLDE.

A major part of the HIE-ISOLDE project is concerned with the upgrade of REX-ISOLDE and it is here that the most clear physics benefits will be found. Nuclear reactions with stable beams have been studied at many different energies, but the key energy region for nuclear structure studies lies around and above the Coulomb barrier. Interestingly, high-energy nuclear reactions with very exotic nuclei have been possible at in-flight separation facilities for more than a decade, whereas the low-energy reactions have only recently become possible for a wide range of radioactive nuclei after several pioneering efforts. ISOLDE has the widest selection of isotopes of all ISOL facilities and a key feature of the REX-ISOLDE complex is that essentially all isotopes produced can be charge bred and accelerated further. The energy upgrade will make them available for reactions up to and above the Coulomb barrier (at present the energy range limits the experimental programme to Coulomb excitation for light and intermediate mass nuclei and transfer reactions for the lightest nuclei). Drawing on the large experience from stable beam work many different experiments are possible, a selection of these is given in the next section that discusses nuclear structure questions from all over the nuclear chart.

Nuclear science touches upon many neighbouring disciplines [IAI02]. Interdisciplinary work has for a long time constituted a substantial fraction of the ISOLDE programme and is also expected to do so in the future. The experimental procedures are in some cases identical to those used in nuclear physics experiments. In other cases rather different procedures are followed and advantage is taken of the variety of pure isotopic beams available at ISOLDE. The two last subsections in Section 2 give a more extensive overview of possibilities at HIE-ISOLDE for nuclear astrophysics and nuclear solid-state physics, but a similar improvement of conditions will also take place for applications in life sciences.

This report focuses on the improvements in the permanent installations at ISOLDE. These of course go hand in hand with the development and upgrade of the dedicated physics instrumentation and introduction of new detection systems, such as a recoil separator for reaction experiments at REX-ISOLDE.

1.4 The role of ISOLDE

ISOLDE is situated at CERN and must fulfil not only CERN's high standards for scientific research, but must also ensure that we do not unnecessarily duplicate efforts made elsewhere. Hence we should consider at least briefly the question of whether ISOLDE *is* the place to make this upgrade or phrased in the words of one of the external reviewers at the NuPAC meeting [NuPAC]: What makes ISOLDE (still) world-wide competitive, if not leading?

The answer lies in the uniqueness of the methods developed at ISOLDE and in the knowledge gathered here. The technical group has a long-standing expertise in target/ion source systems developed for close to 40 years which gives, as mentioned above, the largest variety of radioactive ion beams in present day ISOL facilities. The driver accelerator provides energies above 1 GeV, as foreseen for the next-generation EURISOL facility, and the two target stations allow a fast change-over between different target/ion source systems making ISOLDE the perfect test-bed for future technologies. In fact the planned replacement of the PS Booster by a multi-MW driver, for example the Superconducting Proton Linac [SPL], will be a major step towards realizing EURISOL. Finally, the open, international environment at CERN and the diversity of scientific disciplines present at ISOLDE — nuclear, astro, solid state, surface, atomic, fundamental and bio physics — is a unique combination that along with the on-the-spot expertise in complex experimental set-ups (laser spectroscopy in its various incarnations, mass spectrometry, the RFQ Cooler, the REX-ISOLDE post-accelerator) allows the scientific possibilities to be fully exploited.

Quite apart from the fact that HIE-ISOLDE will provide crucial input for the EURISOL project, the science output alone justifies the efforts. As detailed in the technical report [HIE06] the improvements will be in several directions and will in combination significantly enhance the experimental conditions:

- Increase of the energy of the REX-ISOLDE post-accelerator
- Increase of the primary-beam intensity
- Improvement of the efficiency of secondary-beam production
- Reduction of the background/ improvement of the isobaric purity
- Improvement of the secondary beam optical quality

Adding to this, the continuous improvement in the experimental set-ups to maximize their effectiveness, including the construction of new instruments, secures the competitiveness of ISOLDE at least for the next decade.

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2 Physics case

Studies of the structural evolution, the modification and possible break-down of the concept of shell structure at the dripline, and the investigation of new collective modes of exotic nuclei with extreme neutron-to-proton ratios are a source of fundamental information on the nuclear many-body problem. Many new features have been observed by the exploration of a series of isotopes and isotones, moving away from stability, as for instance new shapes at low energy, phase and shape coexistence, intruder states, new shell closures, non-symmetric nuclear shapes, proton–neutron pairing, and isospin mixing. Learning about the evolution when moving even further away from stability will give access to a deeper understanding of these phenomena.

Nuclear properties are also crucial for the understanding of the reactions leading to the isotopic abundance in the Universe and for the interpretation of astrophysical observables. Understanding the shell structure of these highly neutron-rich nuclei, in particular around the shell closures, is a requisite for the understanding of the r-process.

Finally, pure sources of short-lived radioactive nuclei are used as probes in solid-state physics studies and for fundamental interaction studies.

2.1 *Single-particle states and few-body correlations*

When approaching the driplines the decreasing binding energy and the proton–neutron asymmetry lead to loosely bound quantum systems with different properties than those of stable nuclei. Many aspects of the nuclear interaction are enhanced far away from stability, and one expects novel types of shell structure, new pairing effects, new symmetries and regions with special collective effects. Different phenomena appear, as for instance the halo states, neutron skins, and beta-delayed particle radioactivity.

2.1.1 **Light nuclei: halo and cluster structure**

Light nuclei, in particular the ones close to the nucleon driplines, have played an important role in nuclear structure physics during recent decades and discoveries made in this region have invigorated the field. Many of the experimental activities have taken place at in-flight separator facilities, but ISOLDE has delivered important contributions and first experiments done at REX-ISOLDE promise much for the near future.

In recent years, research on light nuclei has revealed peculiar properties of systems situated at the limits of stability. In some nuclei with an extreme N/Z ratio, neutrons or protons in excess lead to a large spatial extension of the wave function, which develops into halos and skins. In other cases, nucleons are grouped in clusters, in configurations that are reminiscent of molecular structures, with two or more inert centres and valence nucleons to act as exchange particles. These topologies are typically found in states in the vicinity of a threshold for particle breakup. The most significant examples are the ground states of nuclei at the dripline (the halos in ${}^6\text{He}$, ${}^{11}\text{Li}$, ${}^8\text{B}$ and others); however, such structures are also found in stable nuclei, in excited states close to or beyond the breakup thresholds (the 3-alpha clusters states in ${}^{12}\text{C}$, two-alpha and one neutron states in ${}^9\text{Be}$). The cluster structure is a manifestation of the importance of pairing and specific correlation effects, which show up in the diffuse matter distribution of light, weakly bound systems. The description of such a variety of systems represents thus a challenge for models, and at the same time a source of information on the details of the nucleon–nucleon interaction.

The only possible approach (and often a very successful one) for the description of complex nuclei is based on the assumption of a mean field, generated by the mutual interactions between all nucleons. For light nuclei, however, the validity of such a picture is questioned by the small number of nucleons involved. This fact is reflected in the fragility of magic numbers and the abrupt inversion of levels which occurs when the mass number changes even by just one or two units. It is not a surprise, then, that the shell model is not always successful in describing the peculiar properties of light exotic systems.

On the other hand, the limited number of nucleons makes it possible to use a *bare* nucleon–nucleon interaction within true *ab initio* calculations. The Variational Monte Carlo and Green’s Function Monte Carlo methods have been successful in reproducing the structure of bound nuclei up to $A = 10$. Realistic forces are also used in the no-core shell-model which employs a finite harmonic oscillator basis to define the model space. These methods pointed out how three-body forces are necessary for nuclei larger than deuterium. The main limitation for these calculations is their large size, making them not feasible at this time for nuclei beyond $A = 10$. Other microscopic approaches, like the Resonating Group Method, exploit the cluster-structure of light nuclei, still using explicit interactions between all nucleons, but reducing the complexity of the problem by using binary or more complicated few-body cluster bases. The latter models focus on reproducing the characteristics of dilute structures (halos) and on the interplay between halos and the core degrees of freedom.

Halo states need to be close to threshold and therefore the nuclei that exhibit them are close to the nucleon driplines. Proton halos are hindered by the Coulomb barrier and therefore nuclei in the proximity of the neutron dripline are more likely to exhibit halos. There are many well-established halo states for light–neutron-rich nuclei consisting of a core plus one or two neutrons. Most of the experimental studies focus on ground-state halos, as they are easier to observe. Apart from a small binding energy for the valence particles, one of the necessary conditions for the formation of halo states is a small relative angular momentum with respect to the core [Jen04]. Therefore two-body halos occur for nucleons in s or p states, and the same applies for three-body halo states, which are restricted to $K = 0$ or 1, K being the hyperspherical quantum numbers.

Alpha-clusters in light nuclei have been proposed for low-lying states close to the alpha-threshold in some light nuclei. The alpha-cluster states are described as a condensation of weakly interacting α particles in a dilute gas-like structure, and then the alpha particle degrees of freedom, rather than those of the proton or neutron, become relevant. The original proposal for the 7.65 MeV 0_2^+ state of ^{12}C has been extended to states of other $A = 2N = 2Z$ systems like ^8Be and ^{16}O . With the advent of radioactive beams these studies [Yam04] have been broadened in recent years to systems consisting of neutrons in molecule like orbits around alpha-particles.

Experimental investigations in this region can provide information on different aspects. The position, width, and structure of states (spin, parity) are important for comparison with the prediction of the models; but also, the weight of a cluster configuration can guide the choice of the basis wave functions used for the description of a state. Eventually, all information is used to improve the nucleon–nucleon interactions used in the different models.

Reaction studies

The variety and characteristics of beams available at HIE-ISOLDE will allow the application of different methods to obtain the above information. The energy and intensity upgrade will make nuclear reaction methods, for a long time used with stable systems, applicable to exotic

nuclei. In particular, transfer reactions are the tool of choice for nuclear structure studies: in the past, they have been of paramount importance for the progress of our knowledge of the atomic nucleus. Single-nucleon transfer like in (d,p), (p,d), (^3He ,d) lead to a very selective population of states in the recoil nucleus. The Q -value (energetic balance) of the reaction gives information on the position of the states; the angular distribution is related to the spin and parity of the state; the total cross-section gives a measure of the overlap of the structures of the original and recoil nucleus (the spectroscopic factor). Two-neutron transfer reactions like (p,t) or (^{10}Be , ^8Be) can be employed to access information on the pairing properties of nucleons. Another possibility is given by resonant elastic scattering on protons and alpha particles, both with solid and gas targets. The method rests on elastic scattering being the dominant process for resonances with a pronounced single-particle or cluster structure; among other examples, it has been used recently to investigate cluster states in ^{10}Be (see Figure 2.1).

The above techniques require pure beams in a wide energy range to match the conditions for optimal transfer and resonant scattering. A large variety of beams allows the choice of the best reaction mechanism. These characteristics are ensured at ISOLDE by the beam production scheme, which uses fission and spallation reactions on a heavy target, in combination with a Laser Ion Source. For the determination of the parameters of excited states, further help may be provided by the use of polarized beams.

We can identify the following topics where experiments at HIE-ISOLDE could make a significant contribution:

- The study of resonances of systems at and beyond the driplines: position, width, spin, and parity. In some selected cases, the information is crucial in relation to the predictions of models. The disputed observation of excited states in ^7He is one example. Of particular interest is the appearance of new magic numbers ($N = 6, 14, 16$) in neutron-rich exotic nuclei, due to the spin–isospin-dependent part of the nucleon–nucleon interaction.
- Information on halo states and, in the case of two-neutron halos, on unbound subsystems, such as ^{10}Li and ^{13}Be .
- Investigation of new molecular states. Neutron-rich beryllium isotopes constitute an especially interesting case.
- The existence and stability of multi-neutron clusters. This topic can be addressed either using transfer reactions, or breakup reactions of very neutron-rich nuclei.
- The study of position and structure of resonances of interest for astrophysical reactions (see Section 2.5).

The interest in light nuclei also lies in the effects that their characteristics bring to the reaction mechanism. Halo nuclei were identified thanks to the large values for the total interaction cross-sections, and for the narrow momentum distributions of fragments in some of the breakup channels. These static effects are properly accounted for in reaction models for high-energy collisions where sudden processes dominate. At energies around the potential barrier, on the other hand, strong direct channels (breakup, transfer) are observed. It is found that the *coupling* to these channels strongly modifies the interaction potential between projectile and target, with effects on the elastic scattering cross-section (see Figure 2.2) and possibly on the fusion cross-section. The weak binding of the light projectile is at the origin of such effects, through the importance of the breakup channel and the coupling to continuum resonances close to the threshold.

The correct way of describing the reaction process is by using the Coupled-Reaction-Channels (CRC) formalism. Inclusion of the continuum is achieved via a discretization of the momentum space above the breakup threshold [Continuum-Discretized Coupled-Channel (CDCC)]. The method has obtained good results in reproducing cross-sections for elastic scattering and direct processes, while for the calculation of fusion a consistent model has not yet been developed. In addition, only simplified models for the structure of light nuclei can be included in the calculations. Other problems lie in the often poor knowledge of quantities required by the reaction models: the parameters of the potentials for the entrance and exit channels, the importance of relative direct channels, and the structure of states involved in the couplings.

HIE-ISOLDE offers a unique opportunity to improve the understanding of the problem. The areas where experimental information can be obtained are

- Measurement of the elastic scattering of light weakly bound nuclei on different targets in a wide range of energies, in order to derive reliable parameters of the interaction potential. Comparisons with calculated potentials, which include terms due to the couplings (polarization potential), give an estimate of the importance of these effects. Of particular interest is the behaviour of the very weakly bound ^{11}Li halo nucleus.
- Systematic measurements of direct-reaction cross-sections, to establish the relative importance of breakup, transfer and inelastic excitation processes. In addition, methods have been developed in order to extract information on the interaction potential from these measurements, probing a different region (shorter distances) than the elastic scattering alone.
- Measurement of fusion excitation functions, covering the energy range around the potential barrier. Precise measurements are necessary in order to settle the long-standing debate about the effect of breakup on the fusion mechanism.

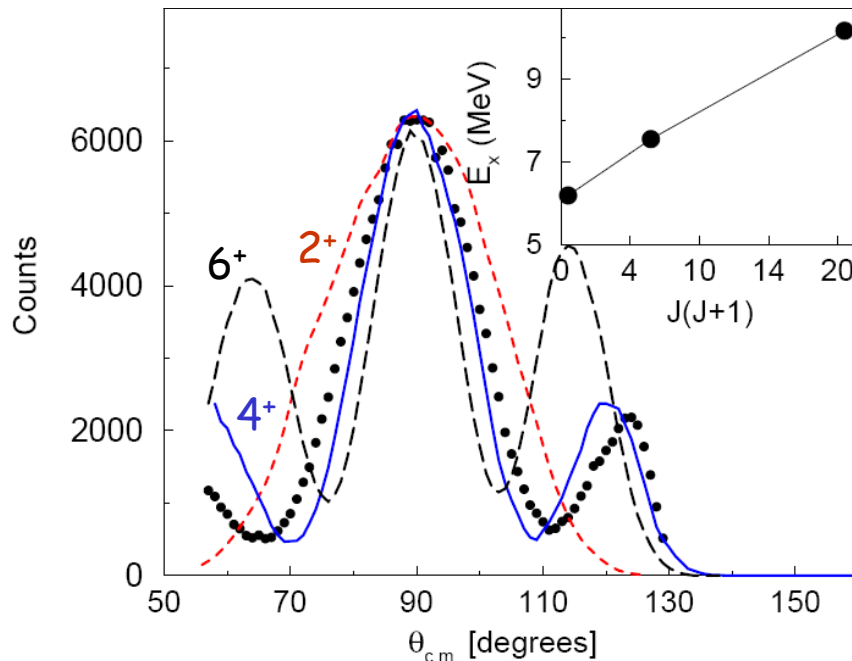


Figure 2.1: Angular distribution of $^6\text{He}+^4\text{He}$ resonant scattering events for the 10.15 MeV state in ^{10}Be . The comparison with simulations indicates that this is the 4^+ state of a rotational band (energy-spin systematics is shown in the inset) built on a state with a α -2n- α structure. From [Fre06].

To achieve these goals, HIE-ISOLDE can provide pure beams at the required energies, allowing measurements around the Coulomb barrier also for the heaviest targets. To obtain excitation functions, a method for varying the beam energy in a simple way would be of great value, since the use of degraders may induce uncertainties and would decrease the quality of the beam. It is important that *exclusive* cross-sections be measured; the different processes can be identified with the use of the MINIBALL γ -array detector and an improved charged-particle detection set-up.

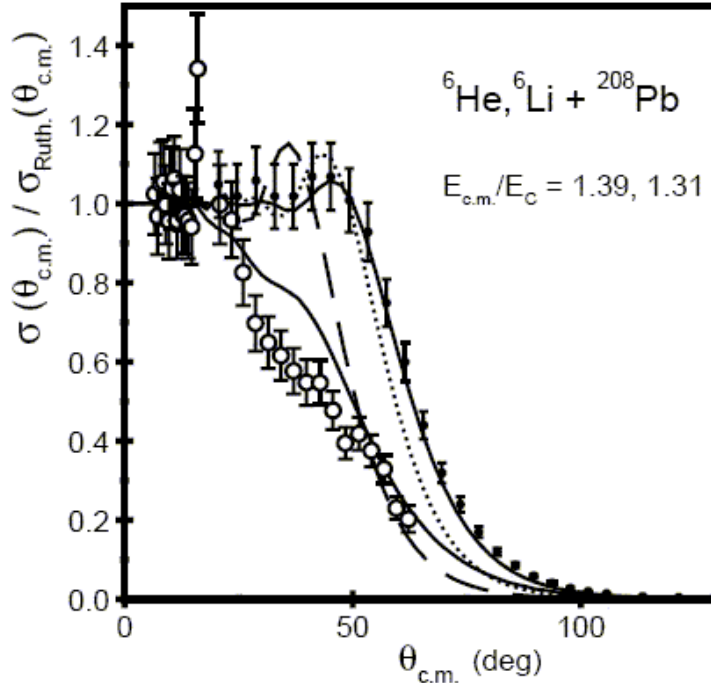


Figure 2.2: Comparison of the angular distributions of the differential cross-section (ratio to Rutherford cross-section) for elastic scattering of ^6He (open circles) and ^6Li (filled circles) by a ^{208}Pb target. Solid curves show the results of the full CDCC calculations while the dotted and dashed curves show the results of one-channel calculations for ^6Li and ^6He , respectively. The difference between the two nuclei is explained by the enhanced importance of the Coulomb breakup for $^6\text{He}+^{208}\text{Pb}$, due to the weakly bound two-neutron halo in ^6He . From [Rus03].

Beta decay studies

Although nuclear halo states can be investigated experimentally via a wide range of techniques, beta-decay experiments, in particular at ISOLDE, have provided an important insight into this interesting phenomenon. In spite of most of the halo nuclei being very short-lived, the ISOL method remains competitive owing to the much higher primary yields and the good optical beam quality, which allows experimental methods not feasible at in-flight facilities. These features are essential for the future HIE-ISOLDE facility. The fact that the primary proton beam is pulsed leads to a characteristic release of the produced nuclei, and this has also proven useful for the separation of signal from background in certain experiments.

Beta-decay is a powerful tool to study halo nuclei, as the halo structure may have a direct influence on the decay. One of the effects is that, owing to the large spatial extension of the halo state, the overlap with the daughter state after the beta-decay may be reduced. Another observable feature is that the halo may decay independently from the core, giving rise to specific decay patterns as in the case of $^{6,8}\text{He}$ and $^{9,11}\text{Li}$ [Nil00], or may lead directly into the continuum [Rii06]. The continuum structure is a key ingredient to the understanding of nuclear halos, in particular neutron ones, as its role increases when the binding energy

becomes smaller. The patterns in the beta-decay are useful to establish the details of the structure of the halo states and the role of continuum in particular. A further source of insight provided by beta decay is the access to exotic β -delayed particle emission. In particular the process of β -delayed deuteron emission has a close connection to the 2-neutron halo state, if one assumes that the 2-neutron pair in s-wave decays into a deuteron by means of a super-allowed beta-decay. This enhances the decay probability and leads to an increased branch of this rare decay. The decay mode, already observed in ${}^6\text{He}$ and indirectly in ${}^{11}\text{Li}$, is an interesting tool to address heavier 2n halo nuclei.

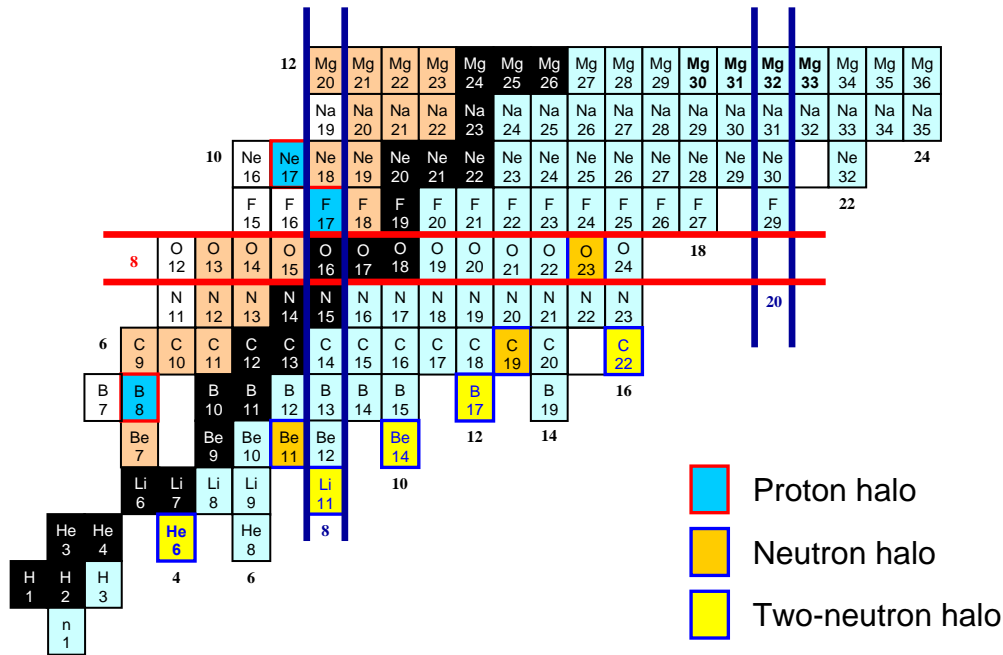


Figure 2.3: The physics at the driplines illustrated by the known proton, neutron, and 2-neutron (Borromean) halo nuclei

There are ongoing quantitative studies of light neutron halos (see Figure 2.3), in ${}^6\text{He}$, ${}^{11}\text{Li}$, and Be isotopes that need to be tested in heavier halos. HIE-ISOLDE will offer the opportunity to challenge the present theoretical approaches in heavier halo nuclei, in a complementary way to other experimental approaches. In particular, increased production yields for C will allow us to test halo states in the carbon isotopes, starting in the loosely bound ${}^{15}\text{C}$. This will lead the way towards the exotic ${}^{19}\text{C}$, where one neutron halo state has been found [Oza01, Cor01]. There are also indications for halo states in O isotopes, which could profit from these developments. In the proton dripline the only well established example of a ground-state proton halo is ${}^8\text{B}$. Nevertheless, there are other outstanding examples like the Borromean ${}^{17}\text{Ne}$ ground state and the one-proton halo ${}^{17}\text{F}$ 495 keV excited state, both linked by a characteristic beta-decay pattern. HIE-ISOLDE will provide an opportunity to investigate these isotopes and to extend the investigation towards the $l = 0$ protons halo states in the sd shell.

The preferred experimental approach towards studying cluster states has been transfer and breakup reactions at intermediate energies. The strength of beta-decay is that it can exploit the selectivity and strong population of such states and the interplay of cluster states in the mother and daughter nuclei. Furthermore, it allows for firm determination of spin by means of correlation studies. In particular, the technique can be relevant for the investigation of cluster effects in nuclei with $N \neq 4n$, which are starting to receive attention, as for instance ${}^{11}\text{B}$ ($2\alpha + t$) [Kaw07]. The studies at HIE-ISOLDE will be relevant for cluster structures selectively

populated by beta decay in nuclei around the well established ^8Be , ^{12}C , ^{16}O , ^{20}Ne , ^{24}Mg and ^{28}Si nuclei.

Ground-state properties

Information about masses, ground-state spins and moments, as well as charge radii is often crucial for understanding the underlying structure of near dripline nuclei. ISOL facilities can play an important role in determining basic ground-state properties of light nuclei, as was recently demonstrated by the measurements of the charge radii in the Li isotopes [San06]. Several examples of measurements of radii and moments are given in [Nil00], but mass measurements can also provide crucial information for accurate testing of the theoretical models of these nuclei. The improved conditions at HIE-ISOLDE for such measurements are given below in Sections 3.1 and 3.2.

2.1.2 Evolution of shell structure

For a long time now, much of nuclear structure physics has been based on the fundamental concepts of single-particle motion in a mean-field potential. Energetic gaps occur in the shell structure at particular nucleon numbers, the so-called *magic numbers*, which to a large extent are determined by the size of the spin-orbit interaction. In recent years, evidence has surfaced that points to changing shell structure with a varying number of protons and/or neutrons. From a theoretical point of view, however, the reasons for this shell evolution are not well established and different scenarios are under consideration; variations in the mean field when approaching the neutron dripline [Dob94] as well as specific components in the residual interaction [Ots05, VRo04] to name a few, see also Figure 2.4. These specific phenomena have a vast influence on the predictions of the nuclear properties far from stability. A classical example is the parity inversion of the ^{11}Be ground state which indicates that the shell gap between the p and sd shells has disappeared. In this case the $1s_{1/2}$ orbital has become the intruder ground state, leading to the vanishing of the $N = 8$ magic number. Another example of such effects occurs in the neutron-rich fp shell. For $Z \approx 20$, the spin-orbit interaction gives a reasonably large gap at $N = 32$ between $p_{3/2}$ and $p_{1/2}$ orbitals, leading to a ‘magic character’ in Ca. This enhanced stability at $N = 32$ does not persist into the shell, and the related shell phenomena, such as relatively high first-excited state, diminish with increasing Z and have actually disappeared by Fe and Ni [Pis01]. An attractive interaction between $f_{7/2}$ protons and $f_{5/2}$ neutrons pushes the latter down in energy between the two p orbitals, thus closing the $N = 32$ gap towards higher Z . This effect provoked a close study of the shell-model interactions in the area leading to new interactions within the full fp shell [Hon01, Hon05]. These calculations are being tested extensively in exotic nuclei throughout the fp shell (for example [Dea05, For05, Jan02, Mar06a]), but there are few tests planned or performed [Bur05, Din05, Ney05] beyond measurements of spin-parities and energy levels.

Recent measurements on neutron-rich nuclei have focused on the $N = 20$ island of inversion, established three decades ago at CERN using ISOL techniques [Thi75]. The limits of this island depend strongly on the behaviour of the effective single-particle energies. In the shell model the evolution of single-particle energies plays an important role in determining the effective interactions between valence particles. Several complementary techniques including Coulomb excitation [Nie05], advanced fast-timing studies [Mac05], and collinear laser spectroscopy [Ney05] have been employed at ISOLDE. Many other regions exhibit similar effects. The studies on this region show that the complementary nature of these approaches enriches our understanding of the evolution of shell structure.

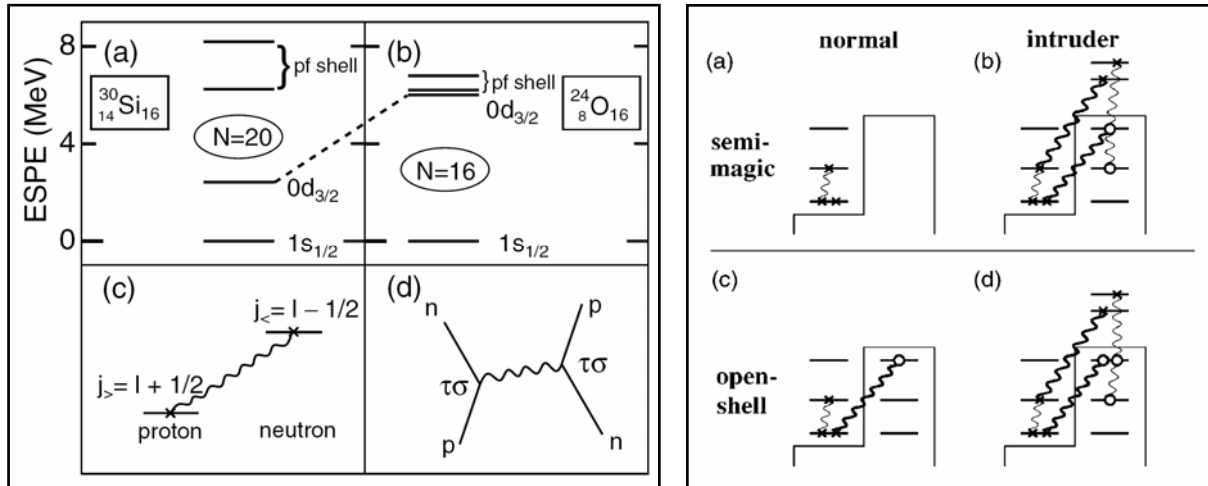


Figure 2.4: Evolution of shell structure in the $N = 20$ ‘island of inversion’. Left panel: Neutron effective single-particle energies for ^{30}Si and ^{24}O , relative to $1s_{1/2}$. The change is due to the strongly attractive $\langle\tau\sigma\rangle$ interaction between a proton in $0d_{5/2}$ and a neutron in $0d_{3/2}$, from [Ots01]. Right panel: Sketch of the sources of the correlation energy of the intruder and the normal states of semi-magic and open-shell nuclei. (From [Uts04].)

The change of effective single-particle energies is governed by the interplay of residual interactions and changes of the mean field. Recently it was pointed out that the tensor force may play a much more significant role in these changes [Ots06]. In order to study predictions of the effect of the tensor force, one can study the energy difference between high- j orbitals as was done for the $\pi g_{7/2}$ and $\pi h_{11/2}$ orbitals in the Sb isotopes [Sch04]. The experimental data show an increasing separation of the two orbitals, as would also be expected for a weakening of the spin-orbit interaction. However, this separation can be explained through the tensor interaction of both orbitals with the $\nu h_{11/2}$ orbital, which is successively filled with increasing neutron number. The mean-field calculations using a Gogny interaction with added tensor force also predict that both proton orbitals approach each other again for very large neutron numbers (> 94), when other neutron orbitals at the top of the shell are filled. While this region of the nuclear chart lies beyond the capabilities of all prospective radioactive beam facilities, it may be possible to study this effect along the $N = 82$ shell closure, where the separation of $\nu i_{13/2}$ and $\nu h_{9/2}$ orbitals as a function of the filling of the proton orbitals can be studied. Owing to the fragmentation of the single-particle strength in the $N = 83$ isotones, transfer experiments are essential for the determination of the distribution of spectroscopic factors. In order to be most sensitive to the high- j orbitals, reactions with large Q -value, such as $(^3\text{He},d)$, and consequently energies in the range of 5–10 MeV/u are needed. It should be pointed out that the beams for $Z > 62$ along the $N = 82$ line, produced via spallation, are unique to ISOLDE.

Beta-decay studies

Beta-decay investigations play a prominent role, as they provide direct information about the level structure and the multipolarity of transitions via correlation measurements or the determination of the internal conversion coefficients. Furthermore, half-lives of excited nuclear states down to tens of picoseconds are accessible by means of the advanced time-delayed (ATD) $\beta\gamma\gamma(t)$ technique [Mac91]. The ATD method, capable of yielding results down to beam intensities of five particles per second, makes use of fast scintillators for gamma detection, carefully calibrated to picosecond precision both for the full-energy peak and Compton events, in combination with HPGe detectors for the selection of decay branches

with good energy. The combined knowledge of the decay properties (transition energies and multiplicities, branching ratios) and the direct measurement of the half-lives provide a model-independent determination of the transition probabilities and therefore direct insight into the nuclear structure. These beta-decay studies allow for systematic studies along isotopic chains with relatively low beam intensities provided the beams are pure.

Areas of exceptional interest concentrate around the $N = 50$, $N = 82$ and $N = 126$ neutron shell closures. Improved intensity and purity at HIE-ISOLDE will provide unique experimental possibilities to study the evolution of shell structure and to observe effects of the coupling between bound and unbound states.

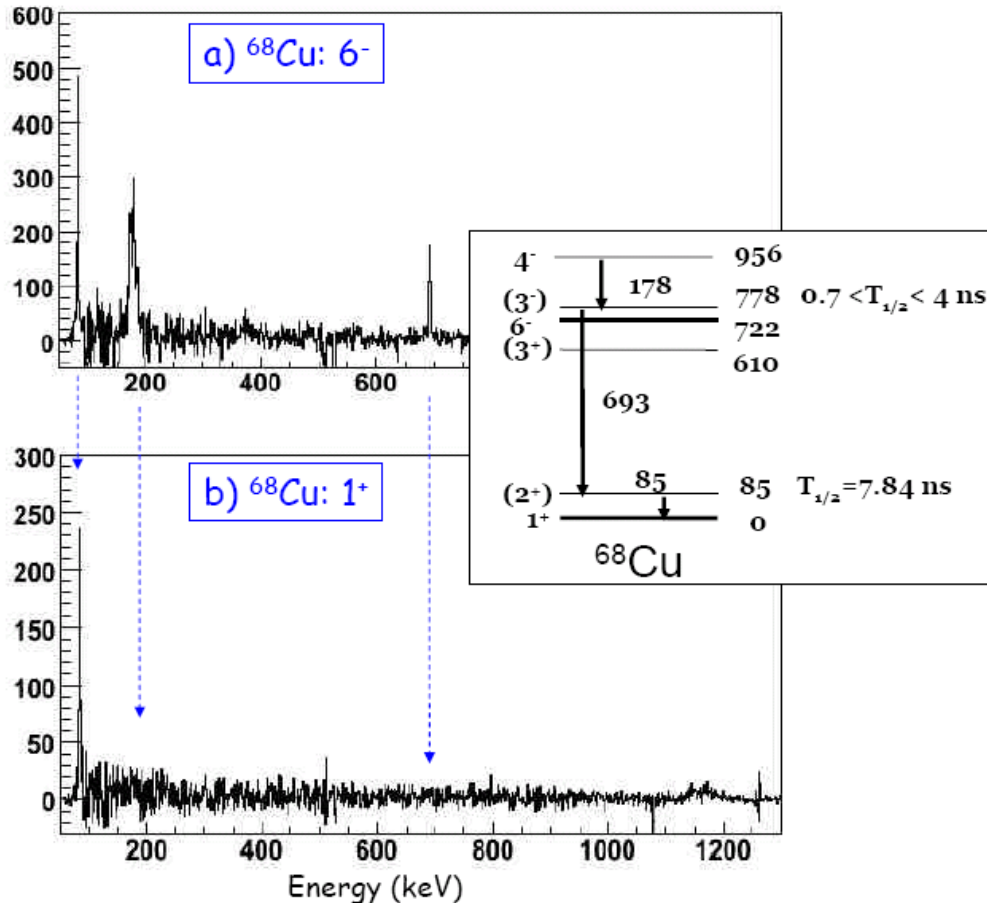


Figure 2.5: Coulomb excitation of isomerically purified beams of ^{68}Cu . The gamma-ray spectrum obtained with the MINIBALL is shown when the lasers were tuned to ionize the 6^- isomer (a) and to ionize the 1^+ ground state (b). The 693, 178 and 85 keV lines that result from Coulomb excitation of the 6^- isomer are present in spectrum (a) while only the 85 keV line from the excitation of the 1^+ state is observed in spectrum (b) [Ste07].

Coulomb excitation

With the availability of a long series of isotopes at HIE-ISOLDE, the evolution of effective single-particle states can be probed. Decay studies, moment measurements, transfer reactions as well as Coulomb excitation supply valuable information to address this particular question. Recently, for example, Coulomb excitation studies have probed the collectivity of even Mg isotopes near the island of inversion at $N = 20$ [Nie05], Coulex measurements of even Zn isotopes up to the semi-magic ^{80}Zn nucleus have been performed revealing information on the strength of the $N = 50$ shell gap close to the doubly magic ^{78}Ni nucleus [VWa07], and the Coulex of isotopically AND isomerically purified copper isotopes have also been performed [Ste07], as shown in Figure 2.5. These measurements probed the strength of the $N = 40$

subshell closure and identified effective proton single-particle states around $Z = 28$ approaching $N = 50$. Similarly, information about the $Z = N = 50$ shell closure has been obtained by measuring $B(E2)$ s for several light Sn isotopes [Ced07]. With the increased energy and intensity of HIE-ISOLDE, measurements of the nickel isotopes, that have higher 2^+ excitation energies [Maz05], should become possible. Furthermore the higher beam energy and the isomeric purification of the laser ion source will allow probing of the transition matrix elements of higher lying states revealing information on the purity of multiplet states originating from a limited number of valence particles around ^{78}Ni . Provided the higher energy is available, similar experiments will be possible with existing ISOLDE beams along and in the neighbourhood of the $Z = 20, N$ and $Z = 50, N$ and $Z = 82$ and $N = 126$ isotopic/isotonic chains.

Single-particle transfer

Neutron addition to neutron-rich exotic beams is a particularly interesting prospect resulting in an even more neutron-rich system. The first neutron transfer experiments have already been performed at REX-ISOLDE with low energies between 2 and 3 MeV/u. An example is the reaction $d(^{30}\text{Mg},p)^{31}\text{Mg}$ which was used to study excited states in ^{31}Mg . This nucleus lies exactly on the border of the so-called island of inversion between the deformed $N = 20$ nucleus ^{32}Mg and ^{30}Mg , which is spherical in its ground state. The single-particle structure of ^{31}Mg is still not fully understood; different theoretical calculations and the experimental data do not provide a consistent picture at this time. Since at the MINIBALL target station charged particles are only detected at forward angles (a set-up optimized for Coulomb excitation experiments), the angular distributions measured in the reaction $d(^{30}\text{Mg},p)^{31}\text{Mg}$ only cover a small range of centre-of-mass angles in the backward direction. These data, shown in Figure 2.6 were therefore not yet sufficient to uniquely identify the transferred angular momentum and thus to clarify the single-particle structure at the edge of the island of inversion and a future experiment with a large angular coverage for the light charged particles is certainly needed.

The Q -values for neutron transfer reactions for stable target nuclei are typically + 5MeV but, with increasing neutron number (decreasing neutron separation energy), Q -values become progressively smaller. For example, the Q -value of the $^{132}\text{Sn}(d,p)^{133}\text{Sn}$ reaction is 0.245 MeV, which corresponds to a neutron separation energy in ^{133}Sn of 2.45 MeV. This leads to a kinematically well-matched reaction with consequent large neutron transfer cross-sections to the final states of ^{133}Sn . The Q -value for the $\text{Ca}(d,p)$ reaction also reduces with increasing neutron number, leading to better matching conditions and therefore larger cross-sections, going at least some way to compensate the decreasing primary yields. Total cross-sections of several tens to a few hundred millibarn are calculated for the (d,p) reactions on beams of $^{49-52}\text{Ca}$ at 3.1 MeV/A [DWU5], making experiments using beam currents $\geq 10^4$ pps possible now for $^{49,50}\text{Ca}$; ^{51}Ca beams are expected with useful intensity after the intensity upgrade. The (d,t) reactions will also yield interesting information on single-particle states below the Fermi surface, albeit in species less neutron-rich than the beam.

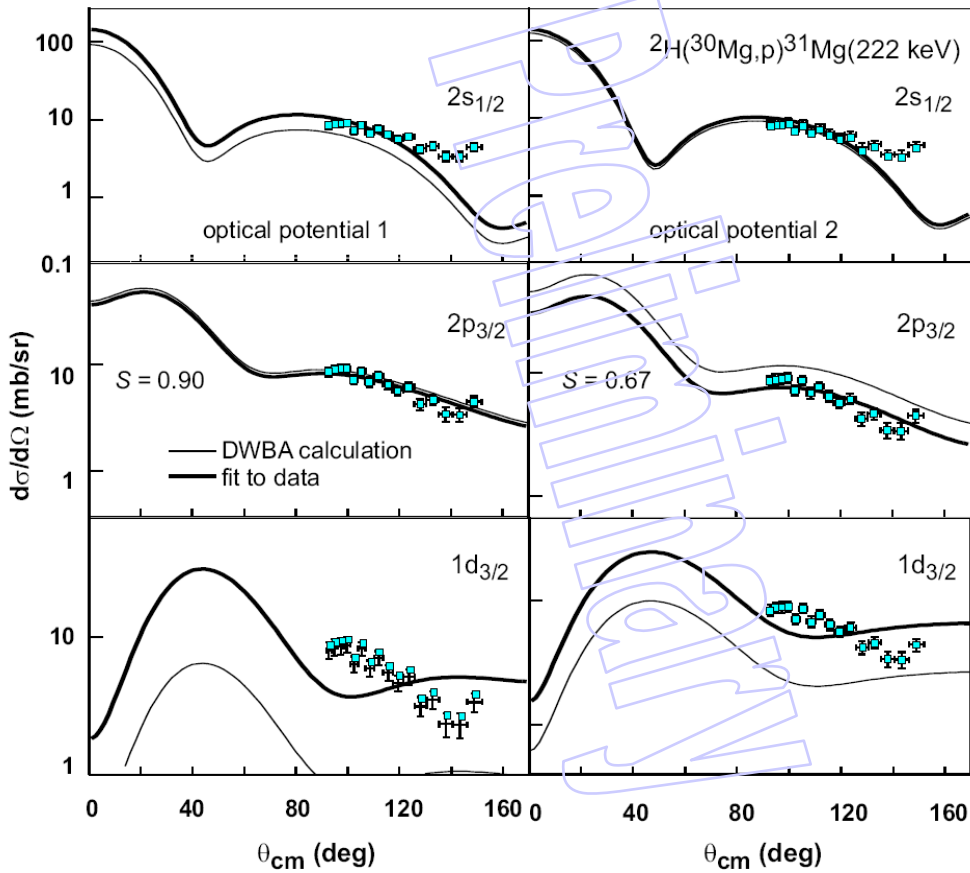


Figure 2.6: Measured differential cross-section of the $^{30}\text{Mg}(d,p)^{31}\text{Mg}$ reaction for the 221 keV excited state in ^{31}Mg , studied at REX-ISOLDE. The state was selected by gamma-ray coincidences using MINIBALL. The experimental angular distributions are compared to DWBA calculations based on different spin assumptions for the level (top to bottom) using two different optical potentials (right and left) [Pan].

Deep-inelastic reactions

Excited states of nuclei can be probed with deep-inelastic reactions [Bro95] using heavy-ion beams at 4 to 5 MeV/u impinging on a heavy target. With the availability of higher energies and the large spectrum of very neutron-rich beams at HIE-ISOLDE, these studies can be extended to neutron-rich radioactive ion beams. For example, beams of neutron-rich Ga, Zn or Cu isotopes accelerated to the above-mentioned energy range and sent onto a heavy target might reveal new information on excited states of the doubly magic ^{78}Ni nucleus and surrounding nuclei [Wal]. It might in fact be the only way in the foreseeable future to study the excited states of the doubly magic ^{78}Ni nucleus. To pursue this line of research new dedicated instrumentation has to be built, e.g., a spectrometer for the outgoing heavy ions.

Ground-state properties

Precision measurements of ground-state properties continue to be a very important source of nuclear structure information, one recent example being the collinear laser spectroscopy study of ^{31}Mg mentioned above [Ney05]. Sections 3.1–3.3 give examples of the technical developments at HIE-ISOLDE that will improve conditions for measurements of masses, spins, and static moments of nuclear ground states and also, in favourable cases, isomers. The present commissioning of the REX ISOLDE facility provides radioactive beams with energies from 300 keV/u to 3.1 MeV/u, allowing heavier-mass nuclei to pass through several tilted

foils at various charge-state and atomic configurations. This will allow a selection of beam energies to obtain possibly higher atomic (and hence, nuclear) polarization. The present results, therefore, pave the way for future determinations of magnetic moments in, for example, proton-rich nuclei in the Fe–Ga region of the f shell for which virtually no information exists on magnetic moments of $N = Z - 1$ nuclei and mirror pairs. As examples we cite the cases of ^{57}Cu that is one-proton removed from the closed ^{58}Ni nucleus and the self-conjugate ^{58}Cu . Another region of much interest is that of the mirror $T = 3/2$ pairs in the sd shell such as ^{21}Mg and ^{21}F .

2.1.3 Isospin symmetry

Isospin mixing is, in principle, difficult to quantify solely from energy spectra but its effects can show up in the electromagnetic transition probabilities of analogue transitions in members of an isobaric multiplet. Electromagnetic transition operators can be split into an isovector and an isoscalar component. For $T \rightarrow T$ transitions, the *geometrical* coefficient describing the vector coupling of isospin determines that the isovector term vanishes if $T_z = 0$ and has equal magnitude but opposite sign for $T_z = +1$ and $T_z = -1$ nuclei. In the case of the $2^+ \rightarrow 0^+$ transition in a $T = 1$ multiplet, charge independence of the nuclear force demands that:

$$\sqrt{B(E2; T_z = 0)} = \left(\sqrt{B(E2; T_z = +1)} + \sqrt{B(E2; T_z = -1)} \right) .$$

This relationship will not be respected in the case of isospin mixing. Such mixing ought to be pronounced in odd-odd $N = Z$ nuclei where $T = 0$ and $T = 1$ states are unusually close in energy. A $T = 0$ admixture in the $T = 1$ states would then give rise to an isovector component in the E2 transition in the $T_z = 0$ nucleus and a consequent deviation from the simple relationship above. Calculations suggest that significant isospin mixing will give rise to a detectable deviation in the $B(E2; T_z = 0)$ value from that predicted by the above equation.

The isospin symmetry in isobars with opposite isospin projection, $T_z = (N - Z)/2$ can also be tested by probing the strength of transitions between two given states, which in case of isobar symmetry should be identical to that of transitions between the analogue states. Therefore the comparison of the strengths of analogue transitions provides a test of the isospin symmetry, and this comparison can be aided by selecting particular states with given quantum numbers. The most suitable transitions are Gamow–Teller, being the simplest test of the isospin symmetric transitions in mirror nuclei with $T = 1/2$ [Fuj99]. The studies can be extended to higher isospin partners by comparing ($T_z = -1 \rightarrow T_z = 0$) and ($T_z = +1 \rightarrow T_z = 0$) transitions in the region of fp shell nuclei.

Beta decay

Beta decay gives access to transition energies and Gamow–Teller strengths up to high excitation energies which can be compared with similar observables obtained in charge exchange reactions with high resolution. The differences yield information on the breaking of the isospin symmetry, which can be interpreted in terms of Coulomb interaction, and on the exotic structures of nuclei far from stability. The study of isospin symmetries in nuclei of the fp and $g_{9/2}$ shells gives information about the isospin mixing in a region where the Coulomb interaction is already large and collective aspects of the nuclear structure are important. The extension of this type of combined beta-decay and charge-exchange reaction studies is of great relevance to determine the robustness of the isospin symmetry and on the mechanisms relevant for isospin mixing.

Coulomb excitation

High-precision Coulomb excitation measurements of the $B(E2)$ strengths to the first 2^+ states in a $T = 1$ isobaric chain will provide a unique insight into the effects of isospin mixing. To detect such an effect is extremely challenging experimentally since the expected differences in $B(E2)$ strengths are rather small and could easily be swamped by systematic uncertainties. There is some, but by no means unambiguous, evidence for a substantial violation of the expected $B(E2)$ relationship from Coulomb excitation measurements at intermediate energies for the $A = 38$ triplet. It would be very important to repeat these measurements at sub-Coulomb barrier energies where the extraction of matrix elements is free from optical-model uncertainties.

2.1.4 Pairing

The pairing of like nucleons in a superfluid condensate is an important and well known aspect of the structure of low-lying states in nuclei near stability. Novel features are expected to appear for very neutron-rich nuclei, leading to changes in the average potential seen by a single nucleon. The phenomenon of nuclear pairing, which causes scattering of pairs of nucleons between energy levels and whose strength is intimately connected with the density of states close to the Fermi surface, can take on a rather more prominent role. A new perspective for the study of short-lived nuclei via transfer reactions is provided by using tritium loaded titanium foils, which can be used for (t,p) reactions in inverse kinematics. With these targets (t,p) reactions can be performed with radioactive beam intensities of 10^6 pps. The probability of the transfer of correlated pairs of neutrons depends on the pairing correlations in both nuclei. With the availability of (t,p) reactions with short-lived nuclei the previous studies that were limited to stable nuclei can be extended along isotopic chains, e.g., the classic example of the Sn isotopes, to very neutron-rich nuclei in order to investigate how the pairing correlations change with isospin.

On the proton-rich side of the line of stability, heavier nuclei with equal numbers of neutrons and protons are expected to provide the first evidence for two further modes of nuclear superconductivity in which the Cooper pairs involve a neutron and a proton. The two additional possibilities arise because, with two particles which are no longer identical, the restrictions imposed by the Pauli principle are lifted. It is then possible to envisage paired states of zero orbital angular momentum in which the intrinsic spins of the nucleons couple either parallel or anti-parallel [Fra00]. The latter mimics the mode seen for like nucleons but the former can only occur for the neutron–proton system. It is not yet clear whether the pairing in this case is strong enough to produce an equal degree of superfluidity but certainly the best nuclei in which to search for its effects are the heavier $N = Z$ systems, where there are strong co-operative proton–neutron interactions, sufficient particles to allow large-scale correlations to develop, and a high level density, allowing easy scattering of pairs between levels. Transfer reactions such as $^{58}\text{Cu}(d,\alpha)^{56}\text{Ni}$ or $^{58}\text{Cu}(p,^3\text{He})^{56}\text{N}$ can be exploited to investigate the degree of neutron–proton correlations in the ground states and excited states of these $N = Z$ systems [VIs05].

2.1.5 Isomeric states

The possibility to selectively laser ionize [VRo04a] and accelerate high-purity isomeric beams with the REX-ISOLDE facility affords a unique opportunity to study excited states built upon isomers in nuclei which are difficult to produce by other methods. A recent focus of studies [Cul98, Cul02, Sch01] has been recoil-isomer tagging of the $N = 77$ isotones in the mass 140 region. Many isomers are known to exist in this region at moderate spins, arising

from competition between the differing shape-driving effects of the neutrons and protons in $h_{11/2}$ shells. For example, in ^{140}Eu [Cul02] the ground state has spin/parity of 1^+ state and a half-life of 1.5 s. At higher energy, there is an isomer with spin/parity of (5^-) and a half-life of 125 ms. Isotopes of interest include ^{137}Nd , ^{138}Pm , ^{139}Sm , and ^{140}Eu which all have appropriate isomers and suitable lifetimes and are produced with yields of 10^6 to 10^7 s^{-1} from the respective ISOLDE primary targets. HIE-ISOLDE will be used to accelerate these nuclei as either isomeric or ground-state beams onto a secondary target of lead. Moderate-spin states will be populated by Coulomb excitation of the ground state or from the long-lived low-spin isomeric states, while transfer reactions can give information on the underlying single-particle structure.

As was demonstrated by recent work at REX-ISOLDE [Ste07], the Coulomb excitation of isomers can lead to induced isomeric depopulation and prompt release of the energy stored in the isomers. The underlying mechanism is a strong quadrupole excitation of the isomer, followed by a cascade of fast M1 or E2 transitions to the ground state. Further investigation of this process in heavier nuclei, which might be of relevance to certain nucleosynthesis scenarios, is possible using the increased intensity and energy of HIE-ISOLDE.

2.1.6 Beta-delayed particle emission

Beta-delayed particle emission occurs for extremely neutron-deficient or neutron-rich nuclei, which are characterized by very high β -decay energy and have daughter nuclei with small particle separation energies. In this way the β -decay populates excited states unbound to the emission of one or several nucleons. If the final states are known, this decay mode allows for information to be obtained on the beta feeding to the different states and the GT-matrix elements by analysing the particle spectra [Poe96]. Moreover, the particle emitting states often have an appreciable fraction of the single-particle strength and hence large width. The distribution of the β -strength in the daughter nucleus determines not only the β half-lives and the rates for β -delayed particle emission but also the shape of the emitted electron and neutrino spectra. The β -delayed particle emission processes are to a large extent understood experimentally and provide very powerful probes for investigations of the nuclear structure at the driplines.

The case of emission of several particles after β -decay, and in particular the $\beta 2p$ ($\beta 2n$) decay, is especially interesting since the mechanism is not completely determined by the energy and momentum conservation laws. Given that it is a three-body break-up there are three binary subsystems, each of them with resonances playing a part in the break-up. The break-up process is then determined by the width of the resonances, the height of the barrier and the structure within the decaying state that can select a given channel. The different proposed mechanisms (sequential, di-nucleon or direct decay) present very characteristic signatures on the individual proton (neutron) distribution, and studies with compact detector arrays in full kinematics can disentangle the different decay paths. Detailed spectroscopy has already been performed for ^{31}Ar , ^{12}C and the $A = 9$ isobars [Bor04]. A very vital programme for studies of this type could be performed with the increased intensity and variety of beams at HIE-ISOLDE, including ^{13}O , ^{17}Ne , $^{20,21}\text{Mg}$ among others on the proton-rich side, and C, N and O isotopes on the neutron-rich side. The studies can be extended to heavier nuclei but then the high-energy resonances fed in the β -decay are very complex and a statistical model approach in the description becomes necessary. The density of particle-emitting levels becomes very high, with an average level spacing much smaller than the experimental resolution. Nevertheless the fluctuations in the spectra still carry information about the underlying level density and systematic studies of this type are meaningful. The study of particle emitting

isomeric states is also of relevance to investigate the different mechanisms leading to nuclear isomerism.

Recently, the beta-delayed fission of certain neutron deficient ^{194}At isotope has been established at GSI. In order to determine the branching ratio of this rare and little understood process, experiments using the more intense beams of neutron-deficient $Z > 82$ nuclei are needed. Also on the very neutron-rich side, north-east of ^{208}Pb , the beta-delayed fission process is expected to occur and the upgrade might allow new investigations in this direction. The understanding of the beta-delayed fission process in this region has a direct impact on the understanding of the ending of the r-process nucleosynthesis path.

The use of spin-polarized beams at HIE-ISOLDE would be a powerful tool to explore the excited states of exotic nuclei populated by beta-delayed particle emission [Hir04]. The method makes use of the angular distribution of the beta decay from a polarized beam, which depends on the emission angle from the polarization axis, the asymmetry parameter of the β transition and the degree of polarization of the parent nucleus. The asymmetry parameter is dependent on the spin and parity of the depopulating nuclear state in the parent nucleus and of the populated state in the daughter nucleus. Once the polarization is determined, the measurement of the angular distribution allows the spin and parity of the daughter states to be assigned. This is a very attractive technique that can be applied to a large variety of nuclei, and which makes use of standard polarization methods like the collinear optical pumping, see Section 3.2.3.

2.2 Evolution of collectivity

2.2.1 Evolution of collectivity throughout the nuclear chart

A straightforward application of Coulomb excitation is a systematic study of the excitation energies and transition matrix elements of low-lying excitations in even–even nuclei. A study of the collectivity in a wide series of isotopes can be compared directly to, for example, beyond mean field calculations [Ben06]. The wide spectrum of different beams allows picking out those isotopes that form critical tests of the models and to highlight, for example, correlation and shell effects or, combined with inelastic proton scattering experiments, to decouple proton and neutron contributions to the nuclear excitation. The latter effect might be evidenced or even dominate the structure in very neutron-rich isotopes.

2.2.2 p–n interaction

The structural evolution in atomic nuclei as a function of the neutron number N and the proton number Z can be largely understood as a result of proton–neutron (p–n) interactions. The p–n interaction also plays an important role for the development of configuration mixing, the onset of collectivity and ellipsoidal shapes in nuclei, single-particle energies and magic numbers, and the microscopic origins of quantum phase transitions in the geometrical shapes of atomic nuclei [Fed77, Hey85, Tal62].

The sum of all nucleonic interactions is reflected by the binding energies. While single differences of binding energies give separation energies, double differences of binding energies can isolate specific classes of interactions. One of them is the average interaction of the last two protons and the last two neutrons, δV_{pn} , for even–even nuclei [Zha88], which is given by the following double-difference equation:

$$\delta V_{pn}(Z,N) = \frac{1}{4} [\{BE(Z,N) - BE(Z, N-2)\} - \{BE(Z-2, N) - BE(Z-2, N-2)\}]$$

where the binding energy BE is defined as:

$$BE(Z,N) = [(Nm_n + Zm_p - m(Z,N)] c^2 .$$

Thus to calculate δV_{pn} values, the corresponding nuclear masses $m(Z,N)$ are required.

The first investigation on δV_{pn} by J.-Y. Zhang *et al.* in 1988 [Zha88] was extended after the latest Atomic-Mass Evaluation (AME) in 2003 [Aud03] which has allowed many more to be calculated. A recent systematic study of the δV_{pn} values [Bre06, Cak05] revealed a number of interesting results such as evidence for an empirical correlation between δV_{pn} values and growth rates of collectivity [Cak06], and intriguing patterns in specific regions of the nuclear chart.

Calculations of δV_{pn} using a simple zero-range δ force [Okt06] can account for some of the experimental δV_{pn} values in the rare earth region but do not work for the actinides [Cas]. However, the recent first large-scale microscopic nuclear density-functional theory (DFT) calculations of δV_{pn} show nice agreement with the overall data trends and even the detailed behaviour in certain mass regions [Sto07]. These calculations are state-of-the-art and make predictions for new masses whose measurements would both provide interesting tests of them in new regions and also help to pinpoint degrees of freedom where the interactions used in these calculations might be improved.

In the vicinity of closed shells one can understand δV_{pn} values in terms of proton–neutron orbit occupations, nl_j , in the shell model. One example is given by the ^{208}Pb region. Figure 2.7 (left) shows empirical δV_{pn} values for this region. It is obvious that there are two trends for $N \leq 126$ nuclei. One of them can be defined for nuclei with $Z \leq 82$, for which the δV_{pn} values increase. This result is expected in terms of nl_j arguments: a shell for normal parity orbits begins with high j (angular momentum) and low n (principal quantum number) and ends with low j , high n . Therefore, just below the $Z = 82$ and $N = 126$ closed shells, protons and neutrons are filling similar nl_j orbits, the overlap between proton and neutron orbits is large, and large δV_{pn} values are expected. The opposite trend can be seen for nuclei with $Z > 82$, which have decreasing δV_{pn} values. Here, low δV_{pn} values occur because the particles are filling dissimilar orbits. There is also a sudden increase just after $N = 126$ in Figure 2.7 (left), where protons and neutrons are added just above the $Z = 82$ proton and $N = 126$ neutron closed shells. Again, large δV_{pn} values are expected. As can be seen from Figure 2.7 (right) there is a lack of data for more neutron-rich nuclei, for which it would be very interesting to obtain information on the proton–neutron interaction.

By extending precision mass measurements to nuclei in the regions where no δV_{pn} values can be determined so far, it will be possible to test the predictions of modern theoretical models in detail.

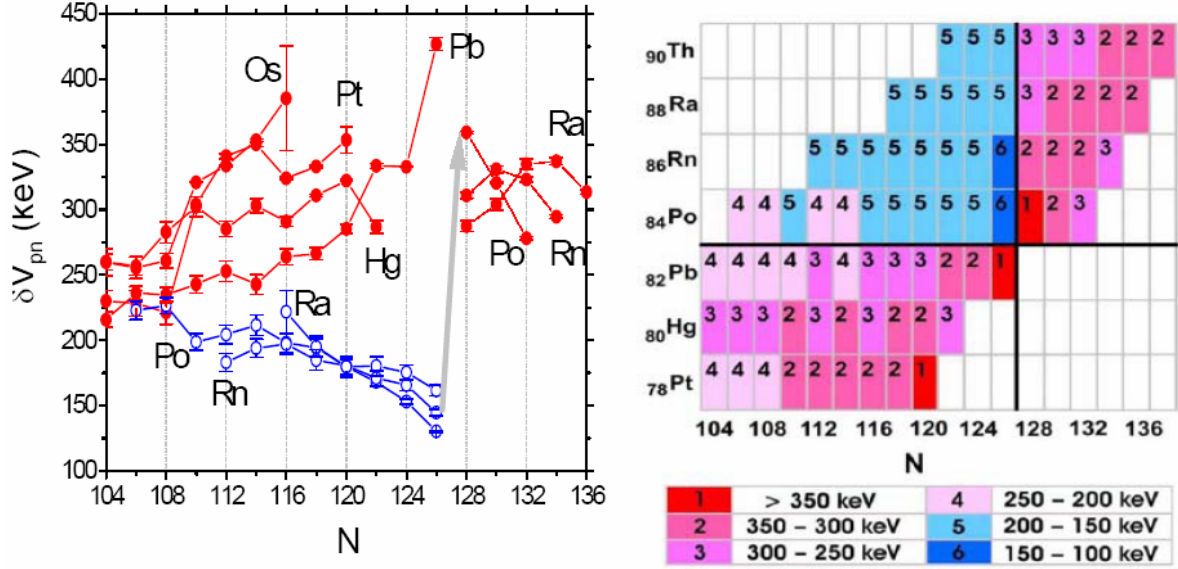


Figure 2.7: Left: Empirical δV_{pn} values for the ^{208}Pb region. Red and blue colours emphasize changes in δV_{pn} depending on the nl values in the proton and neutron orbits, respectively. The grey arrow shows the sudden jump at $N = 128$ (based on Ref. [Cak05]). Right: Colour coded δV_{pn} values in a $Z-N$ chart for the same nuclei as in the left-hand figure (based on [Cak05]).

2.2.3 Shape coexistence

It is a surprising feature that for certain numbers of neutrons and protons, a subtle rearrangement of a few nucleons among the orbitals at the Fermi surface can result in a dramatic change of the nuclear shape. The phenomenon of *shape coexistence* in which very different shapes (spherical, prolate deformation or the rarely observed oblate deformation) have similar excitation energies has been discussed extensively in two regions in the periodic table: the region around $N = Z = 34$ and 36 where there are predicted to be large shell gaps at oblate and prolate shape for these nucleon numbers [Fis00], and neutron mid-shell nuclei near the $Z = 82$ shell closure. In descriptions of this effect using mean-field and beyond mean-field approaches it appears that the details of the energy spectrum are very sensitive to the monopole field, the strength of the proton–neutron quadrupole field and the pairing. From an experimental viewpoint, the interpretation in terms of geometric shapes is appealing but so far has been inferred mostly from in-beam γ -ray spectroscopy and α -decay studies.

In the $A \sim 70$ region, the shape-coexistence phenomenon has been documented for the light krypton isotopes in recent years with observation of a doubling of states, associated with the different shapes, in particular the observation of a low-lying excited 0^+ state [Bou03]. The nucleus ^{70}Se ($Z = 34$, $N = 36$) has recently been studied using Coulomb excitation at REX-ISOLDE [Hur07]. This measurement has allowed the sign of the spectroscopic quadrupole moment to be inferred for the first 2^+ state in ^{70}Se . This measurement appears to refute the predicted existence of an oblate shape in this case, and indicates that the behaviour of the Se nuclei is qualitatively different from the Kr nuclei. The key to a complete understanding of these issues would be to push the Coulomb excitation technique to the limits, with studies of the $N = Z$ nuclei ^{68}Se and ^{72}Kr . Such experiments would seek to identify the sign of the spectroscopic quadrupole moment, by fixing the value of the transition matrix element to that measured independently at intermediate energies [Gad05]. These experiments will only be possible with the increased yield and selectivity arising from HIE-ISOLDE.

The region around the neutron mid-shell near the $Z = 82$ shell closure exhibits especially clear indications of competing individual and collective behaviour at low-excitation energy (for a recent review, see [Jul01]). For neutron-deficient nuclei having $Z \sim 82$, shape coexistence was first observed when isotope-shift measurements carried out at ISOLDE for Hg nuclides revealed a sharp transition between ^{187}Hg and ^{185}Hg . This change was interpreted as a transition from a weakly oblate shape to a more deformed prolate structure [Bon76, Fra75]. Nowadays, there exists a large body of experimental information supporting the picture of coexistence of different shapes at low excitation energies in lead isotopes and its neighbours. Spectacular evidence for shape coexistence has also been seen in the neighbouring light lead nuclei such as ^{186}Pb [And00], where two low-lying 0^+ excited states, associated with the oblate and deformed prolate shape, have been found in the same nucleus. Recent in-source laser spectroscopy measurements at ISOLDE have allowed the mean square charge radii be deduced down to ^{182}Pb and have shown that the lead nuclei stay essentially spherical in their ground state [Wit07]. Such studies, also giving nuclear moments, can be extended to the n-deficient and n-rich side $Z > 82$ nuclei provided effective laser ionization schemes can be developed. These data are crucial to understand the evolution of shape coexistence when moving away from the $Z = 82$ proton closed shell.

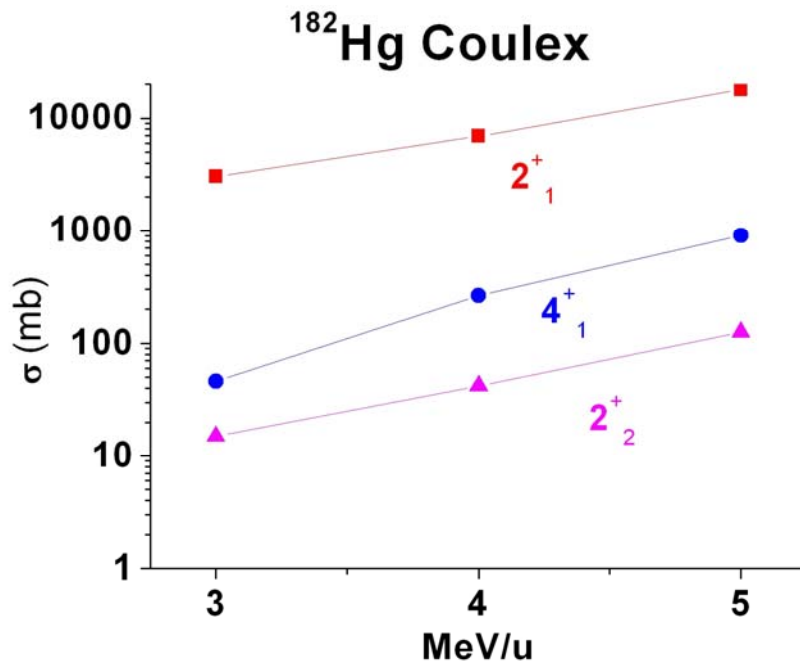


Figure 2.8: The cross-section for Coulomb excitation of the ^{182}Hg beam onto a ^{xy}Zy target is shown as a function of beam energy. Almost an order of magnitude increase in cross-section for the two-step Coulex towards the 4^+_{1} state is observed.

Coulomb excitation

While much has been learned in recent years concerning the behaviour of nuclear shape coexistence, several key questions remain, such as the degree of mixing between the various different configurations. Embarking on a study of nuclei such as $^{182,184}\text{Hg}$ where the co-existing configurations lie closest to each other [Jul01] would allow these questions to be addressed. As was demonstrated recently, the required charge state necessary for post-

acceleration of very heavy nuclei can be achieved at the REX-EBIS charge breeder [Wen07]. First exploratory experiments were performed, but a full delineation of the problem can only be done when the higher energy is available (Figure 2.8). In order to address the questions related to shape coexistence, Coulex is an attractive technique: (i) it will preferentially excite states strongly coupled to the ground state so that non-yrast excited states will be readily observed; (ii) the sign of the diagonal quadrupole matrix element can be deduced so that prolate and oblate deformations can be distinguished; (iii) the degree of collectivity in a rotational band (deformation parameter) and mixing between different structures can be determined directly from the transition matrix elements.

Other studies

The Gamow–Teller (GT) decay, in particular, is well known to be highly sensitive to the configurations of the nuclear states. A successful method of investigating the nuclear deformation stems from mean field calculations [Ham95, Sar01] that predict that the GT decay mode is sensitive to nuclear ground state deformation. The calculation for even-even nuclei in the $A = 70$ region gives strong differences in the total intensity and energy distribution of the GT strength depending on the shape of the parent nucleus. Therefore the measurement of the beta-decay strength, which close to the driplines is expected to be mainly located in the Q -beta window, will provide information on the deformation. The traditional high-resolution technique for detecting gamma-rays after beta-decay with HPGe detectors fails to detect fragmented strength in high excitation energy in the daughter nucleus, which still carries a significant part of the strength. The alternative method proposed is an accurate measurement of the $B(\text{GT})$ as a function of the excitation energy in the daughter nucleus by means of total absorption gamma spectroscopy. The method has been successfully applied to several nuclei in the Sr–Kr region at ISOLDE [Nac04, Poi04]. An expansion of the technique can be successfully applied at other areas of strong deformation and shape co-existence at HIE-ISOLDE, starting with the Pb–Hg region.

Another powerful method, applied successfully in the region above Pb, has been studies of alpha decays [VDu00, Kar06]. A continuation of these studies will be possible with the improved beam conditions at HIE-ISOLDE. This will also be the case for the measurements of ground (and isomeric) state properties by laser spectroscopy, be it via collinear beams laser spectroscopy or via in-source laser spectroscopy as performed recently for the light Pb isotopes [Wit07].

2.2.4 Octupole shapes

There are experimental and theoretical indications of the existence of regions where strong octupole correlations take place in the presence of an intrinsic nuclear quadrupole deformation [But96]. Such correlations, leading to reflection asymmetric shapes in the extreme case, have their microscopic origin in the proximity of single-particle orbitals differing by three units of angular momentum and close to the Fermi surface. The best conditions occur in the actinide region around $A = 225$, where the close lying $g_{9/2}$ and $j_{15/2}$ neutron orbitals and the $f_{7/2}$ and $i_{13/2}$ proton orbitals lead to the enhancement of the octupole correlations, and strong experimental signatures of octupole collectivity have been found.

Experimental studies in the $A = 225$ region are essential to understand the mechanism of the disappearance of the octupole deformation and the interplay between quadrupole and octupole collectivities. Some of these nuclei will become accessible via Coulex and beta-decay [Aas96, Fra01], providing access to level schemes, to the multipolarities of the transitions, and more importantly their transition rates. The latter can be obtained in a model-independent way by

the Coulex yield or by direct measurement of the half-life of the excited states via the ATD method (see Subsection 2.1.2). A systematic mapping of the region will be possible at HIE-ISOLDE, where a large number of isotopes will be available with good intensities. Such studies provide insight into the interplay of the quadrupole and octupole collectivities, and on the role of collective versus single-particle effects. They can be extended to other areas of interest as already initiated in the $A \sim 150$ region of the table of nuclei.

2.2.5 Pygmy resonances

In heavy, neutron-rich, nuclei the steadily increasing neutron excess results in the development of a mantle, or skin, of neutrons on the outside of the nucleus. The eventual thickness achieved by this skin is still a matter of theoretical conjecture, and is obviously related to the position of the dripline itself, but its formation has some intriguing consequences. Firstly the outer neutron skin would represent effectively a new form of nuclear matter; in normal nuclear matter the proton and neutron radii are equal and the two distributions overlap. Pure neutron matter is found only in neutron stars. Secondly, the formation of a skin opens up the possibility of new modes of collective motion. Collective modes are already known to exist in normal nuclei in which the proton distribution oscillates against the neutrons (giant dipole resonance excitations). New modes are possible which involve oscillations of the skin against the core, so-called ‘Pygmy’ (dipole) resonances.

Recently, experiments using 500 MeV/u $^{130,132}\text{Sn}$ beams carried out at GSI have given evidence for resonance-like structure at an excitation of 10 MeV which is interpreted as Pygmy excitations in these nuclei [Adr05]. These experiments were able to measure the dipole strength distribution for excitation energies above the neutron threshold. Real-photon measurements on stable nuclei have revealed a concentration of E1 strength in bound states, spread over excitation energies between 5.5 and 8 MeV [Zil02]. The availability of intense neutron-rich Sn beams at energies up to 10 MeV/u at HIE-ISOLDE will allow the collective electric dipole strength to be probed at excitations *below* the neutron threshold for *exotic* nuclei. For these nuclei, the large collective strength of these resonances (several W.u.) makes them observable in heavy-ion Coulomb excitation at bombarding energies of 5 MeV/u (10^{-3} of the 2_1-0 transition intensity); the yield would be increased considerably at 10 MeV/u.

2.3 Order to chaos

The beta-delayed particle spectra change from a broad distribution due to a few wide levels for very light Z to distant narrow levels when the single-particle strength is highly fragmented, and further to a bell-shape distribution for higher Z (Figure 2.9).

The high energy available for the β -decay of nuclei far from stability not only leads to the possibility of populating states above the threshold for particle emission, but also gives access to nuclear excited levels of extreme complexity. A situation frequently encountered is that individual levels are still separated, that is the width is smaller than their spacing, but hardly resolvable in experiments. The complexity is such that the most profitable approach is describing the nuclear structure in terms of local averages and fluctuations around them. These fluctuations in nuclear level widths and level spacing can be described by general statistical laws and are characteristic of the phenomenon of deterministic chaos in nuclei. The fluctuations in the spectrum provide an interesting method to determine level densities in exotic nuclei, see, for example, [Gio00].

For the heavier delayed-particle emitters, the individual levels are narrow, but in the high-energy part of the excitation spectrum where the delayed particle originates, the level density is very high and the structure of the states very complex. For such states (p, n- or α -emitting) the best description is in terms of the compound nucleus model. Detailed spectroscopic studies in neutron-deficient nuclei from Ar to Kr will be of interest to determine when and how the transition from order to chaos occurs.

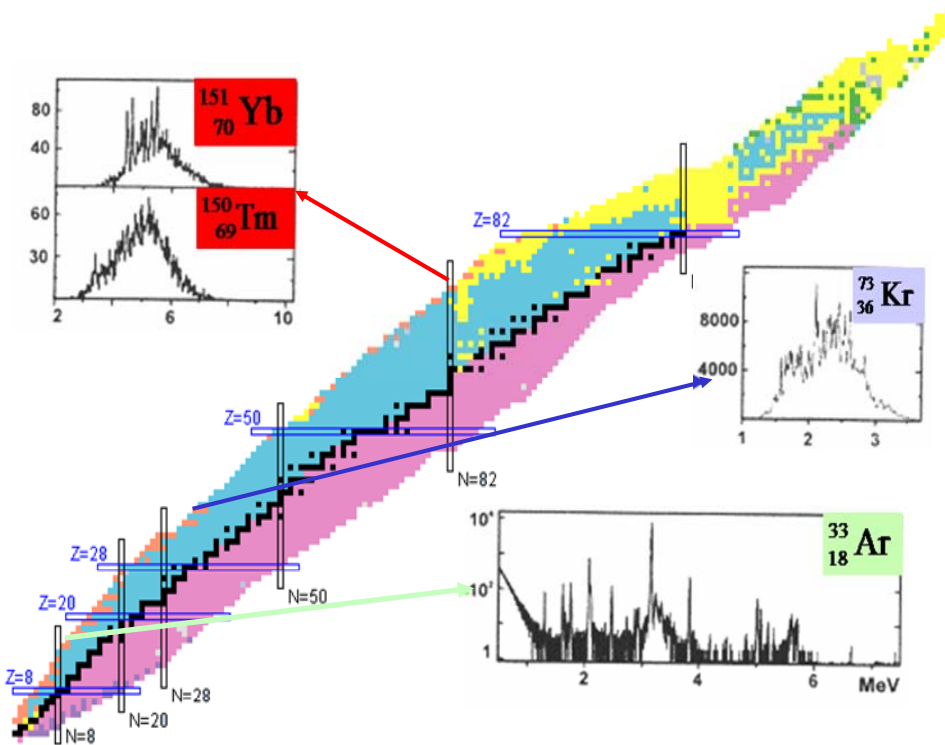


Figure 2.9: The transition from order to chaos is illustrated by the increased complexity of the delay particle spectra for proton-rich nuclei

2.4 Standard Model tests

Low-energy tests of the Standard Model are an important complement to results obtained in experiments at high energies. If new physics is observed at the LHC or other colliders, the findings can be tested in experiments at low energies, which in addition can supply further information on the nature of the interaction and the particles involved. Examples of possible types of new physics at tree or loop level for which information can be obtained from low-energy experiments include heavy quark mixing, charged Higgs boson (H^\pm) decay, heavy W bosons, right-handed W boson (W_R), Z' loops, supersymmetric loops and others [Eid04].

Tests of fundamental symmetries, in particular parity (P) and the combination of charge conjugation and parity (CP), can be performed in nuclei by determining the correlations between different spin and momentum vectors of the particles participating in nuclear β -decay processes, which are very sensitive observables to scalar and/or tensor contributions to the weak interaction. Nuclear β -decay experiments have previously led to the discovery of a number of fundamental properties of the weak interaction, like parity violation and the axial-vector structure of the interaction [Sev04, Sev06].

The Standard Model of the electroweak interaction can be tested in super-allowed Fermi β decays by high-precision measurements of observables leading to ft -values. Theory is able to precisely describe such transitions, but corrections are needed since decays take place in the nuclear medium. For a significant comparison between experiment and theory, the precision needed on the ft -values is of the order of 10^{-3} – 10^{-4} , and this is the precision required for the measurement of the Q_β value, the β -decay half-life, and the super-allowed branching ratio [Har05]. This goal has been achieved today for 13 nuclei ranging from ^{10}C to ^{74}Rb . An Ft value can be obtained for each nucleus from the ft by applying radiative and isospin breaking theoretical corrections, which are actually the limiting factor for the required precision. The combined Ft value allows determination of the weak vector coupling constant G'_V and, by a comparison with the purely leptonic decay of the muon, of the V_{ud} matrix element of the Cabbibo–Kobayasha–Maskawa (CKM) quark mixing matrix. The weight of the different corrections is dependent on the nuclear mass and therefore the extension of the measurements to heavier nuclei is crucial for this type of test. Improved data also for lighter nuclei are of importance to improve our understanding and the modelling of the electroweak interaction. Recent scientific highlights include the mass measurements of ^{32}Ar ($T_{1/2} = 98$ ms) [Bla03], ^{74}Rb ($T_{1/2} = 65$ ms) [Kel04], and ^{22}Mg [Muk04]. In order to perform high-precision beta-decay studies of this type, yields of the order of at least 10^3 particles per second are required, which will be within reach of the HIE-ISOLDE facility.

Another way of testing the electroweak Standard Model at low energies is to perform measurements of correlations involving the energies, spins, and momentum vectors of the nucleus and the leptons participating in the beta decay process. Measurements of the beta–neutrino correlation with unpolarized nuclei and of the beta-asymmetry parameter in the decay of polarized nuclei are sensitive to exotic (i.e. scalar and/or tensor type) contributions to the weak interaction. The first are in principle best suited to study possible scalar charged weak currents, while the second are ideal to test for tensor-type charged currents. In the last decade the use of ion and atom trapping techniques have triggered a revival of beta–neutrino correlation measurements, now permitting sub-percent precision [Bec03, Gor05, Rod06]. At ISOLDE such measurements have recently become possible with the newly installed WITCH experiment. Currently a new technique to reach a similar precision also in beta-asymmetry parameter measurements is also being developed [Kra05]. At ISOLDE this new method is being applied and further improved at the NICOLE experiment which uses low-temperature nuclear orientation to polarize the nuclei. For beta-asymmetry parameter measurements nuclei with a single-branch pure GT transition of low endpoint energy are best suited. For beta–neutrino correlation measurements with a Penning-ion-trap-based system (e.g. WITCH) several of the 13 well studied super-allowed Fermi beta decays (e.g. $^{26\text{m}}\text{Al}$, ^{46}V and $^{38\text{m}}\text{K}$) as well as several of the $T = 1/2$ mirror nuclei (especially ^{25}Al , ^{33}Cl and ^{35}Ar) are best suited. The super-allowed character of all these transitions guarantees that nuclear structure related effects are small and sufficiently well under control. For these correlation measurements very pure beams and yields of at least 10^7 particles per second are required. These will be available at the HIE-ISOLDE facility.

The uniqueness of HIE-ISOLDE for this type of experiment resides on the one hand in the wide range of isotopes that are available, allowing the selection of nuclear states that are best adapted to the physics purpose, i.e., maximizing the sensitivity to new physics while avoiding or even eliminating nuclear structure effects, and on the other hand in the high yields, as high statistics is a necessary prerequisite for any precision measurement. This work is a natural extension of the studies accomplished at present at ISOLDE, which include mass, branching ratios, and half-life measurements contributing to the ft -values of the superallowed $0^+ \rightarrow 0^+$

transitions, and beta-neutrino correlation measurements and determination of beta-asymmetry parameters in measurements of correlations in beta decay.

Other possibilities exist for experiments related to Standard Model tests at HIE-ISOLDE which have not yet been exhausted. An example is the measurement of atomic parity violation and the determination of an anapole moment with francium, which would provide insight on a possible Z' boson and on specific leptoquark scenarios, and is currently being prepared both at Stony Brook and at Legnaro. The full setting-up and tuning of the experimental apparatus can be done at these laboratories, but sufficiently high yields to reach the required level of precision are at present and also in the foreseeable future available only at HIE-ISOLDE. Other low-energy experiments testing predictions of the Standard Model are the EDM experiments searching for exotic interactions by trying to identify new sources of CP violation and for which nuclei can provide extra enhancement of sensitivity, for instance in the case of Ra.

2.5 Nuclear astrophysics

Nuclear astrophysics, a key interdisciplinary applied field of nuclear physics, is concerned with the mechanism of energy production in stars and the production of elements in the Universe. Elements are produced as a result of nuclear reactions. Many studies have been performed elucidating the production of the elements up to the iron region in normal stellar environments. However, what is still not well understood is the production of elements beyond the iron region. Nuclear reactions that occur in an explosive stellar environment are believed to play a role in the production of these heavy elements as well as some light elements. Stellar explosions such as novae, supernovae, and X-ray bursts are cataclysmic events that produce energy rapidly at great rates and also release these elements into interstellar space. High temperatures and densities, with time scales of the order of seconds characterize such scenarios. Rates of nuclear reaction increase at these higher temperatures and occur much faster than in quiescent stars. The pathways of such reactions clearly involve short-lived radioactive/exotic nuclei. Because such nuclei have fast beta decay lifetimes, the sequence of reactions is dependent upon a balance between capture/fusion reaction rates, and either beta decay or photodisintegration processes. Given these conditions, the reaction pathways move close to the driplines of particle stability. The properties of exotic nuclei and their interactions are crucial to understanding these cataclysmic stellar explosions. Such knowledge is currently incomplete, but with the onset of the next-generation radioactive beam facilities such as HIE-ISOLDE, leading to much higher intensity beams, higher projectile energies and with more desirable properties such as higher purity and beam characteristics, our understanding of these explosive phenomena will increase and allow us to address one of the fundamental questions today; namely, how – and where – are the elements heavier than the iron region produced.

The nuclear processes occurring in exploding stellar scenarios are similar to but involve different, more exotic nuclei than in quiescent stars: they are faster, involve higher temperatures and occur primarily along the limits of particle stability (the driplines). As hundreds of different reactions involving such exotic nuclei are involved, it is clear that current knowledge is very incomplete. In the past it has been impossible to measure reaction rates of radiative-capture and particle-transfer reactions involving short-lived radioactive species. With the advent of radioactive beam facilities, such difficult types of studies can be pursued. The type of information needed to improve our understanding of complex reaction pathway codes includes not only reaction rates especially for reactions involving low- Z species, but also nuclear masses, excited state properties (such as exact excitation energy,

width, lifetime, spin and parity), decay scheme data, electron-capture rates, neutrino- and photon-interaction rates, and particle reaction rates (transfer, elastic scattering, etc.). Reaction rates can be dominated by strong resonance reactions in situations in which the energy spacing between levels is higher than the energy widths of levels. In the reverse situation, Hauser–Feshbach types of calculations seem to be acceptable.

As a result of obtaining the types of data described above, the mechanisms of astrophysical processes such as the rp process, the s process, the r process, and the p process can be better understood and, in turn, we can provide better calculations of elemental abundances in the Universe for comparison with measured abundances.

This section will summarize some of the types of experiments that will be possible with the new HIE-ISOLDE facility and illustrate the knowledge that could be obtained. There are a large number of review articles that provide insights into our present understanding of such events as core collapse supernovae, classical nova outbursts, X-ray bursts and type 1A supernovae [Woo86, Jos05, Nup04]. The focus here will be to provide some specific details on how particular experiments involving radioactive beams at HIE- ISOLDE may provide knowledge about these events. In these examples the scientific rationale in terms of what can be learned will be summarized along with some details of the study. The connection between the updated features of HIE-ISOLDE and the capability of now attempting such studies will also be addressed.

There are many experimental techniques which can be used and applied to studies involving exotic nuclei [Blac05]. Indeed with the first-generation radioactive beam facilities such techniques have been used and new ones developed taking advantage of unique features of working with such rare and unstable beams. In this section a summary of such techniques will be covered with particular emphasis on techniques that are more universal regardless of the nuclear region of interest. Such techniques include mass measurements, decay scheme and nuclear spectroscopy studies, and related types of studies. These will be summarized here along with some of the projected studies.

2.5.1 Novae, X-ray bursts and the rp process

Novae explosions (explosive hydrogen burning on the surface of an accreting white dwarf in a binary stellar system) and X-ray bursts (explosive hydrogen burning on the surface of a neutron star in a binary stellar system) are rapid processes and involve nuclei on the proton side of stability. Novae occur at lower temperatures and involve self-contained mini-reaction networks while X-ray bursts occur at higher temperatures with breakout of the localized networks, leading up to the rp process. In both cases the key reactions are radiative proton captures and beta decay. Breakout to the rp process still requires more knowledge of the pathways and reactions rates of the individual reactions, which involve short-lived radioactive reactants. The rp process encompasses a sequence of proton-capture reactions and β^+ decays on the proton rich side of stability. This process plays a role in novae and X-ray burst explosive scenario in stars. The understanding of this process requires a detailed knowledge of certain radiative proton and alpha capture reaction rates, (p, α), (α ,p) reaction rates and β^+ decays. The reactions below play key roles in one or more of these processes.

²⁶Al in the Universe

An important question in nuclear astrophysics concerns the production site of the γ -ray observable isotope ²⁶gAl (7.2×10^5 y) in the Universe. A significant amount of this (short-

lived on a galactic scale) isotope has been observed by orbiting γ -ray observational satellites such as HEAO-3, COMPTEL, and now INTEGRAL and the production site is still the subject of much debate. A large uncertainty in determining the production rate is due in part to the uncertainties in key nuclear reactions, namely $^{26g,m}\text{Al}(p,\gamma)^{27}\text{Si}$ and $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$. Recently, the rate of the $^{26g}\text{Al}(p,\gamma)^{27}\text{Si}$ reaction at novae temperatures was measured directly in inverse kinematics with an intense ^{26g}Al beam ($\sim 5 \times 10^9 \text{ s}^{-1}$) and using the DRAGON facility at ISAC [Rui06].

Given a relatively intense beam ($>10^6 \text{ s}^{-1}$) of either $^{25,26m}\text{Al}$ at HIE-ISOLDE, elastic/inelastic scattering studies and transfer reactions will be performed which are of importance to determining key parameters of radiative proton capture reactions on these key nuclides. The rate of this reaction is thought to be dominated by resonances (not direct capture), whereby the rate is dominated by the resonance strength $\omega\gamma$ and the temperature. It has been shown that the largest uncertainties in the $^{25}\text{Al}(p,\gamma)^{26}\text{Si}$ rate are the uncertainties in the resonances of ^{26}Si that lie $< 1 \text{ MeV}$ above the proton threshold (5.518 MeV) in ^{26}Si . Additional data is needed on the gamma and proton partial widths of these states in order to deduce the reaction rate in the absence of a direct proton capture experimental study.

The short lived ($T_{1/2} = 6.35 \text{ s}$) isomeric state ^{26m}Al is formed via the $^{25}\text{Mg}(p,\gamma)^{26}\text{Si}$ reaction as well as the beta decay of ^{26}Si (see above). This reaction is not directly important for the destruction of ^{26g}Al . However, a better understanding of the role of this reaction could be an important part of nucleosynthesis studies since abundance ratios in the Al–Si range may be affected in supernovae scenarios rather than novae. The existing data on the isomeric reaction rate are mostly based on Hauser–Feshbach calculations. In order to ascertain the existence of resonances in the $^{26m}\text{Al} + p$ system, it is proposed that a resonant elastic scattering study be performed, followed by appropriate transfer reactions to ascertain properties of the key resonant states.

Assuming the development of appropriate beam intensities of $^{25,26m}\text{Al}$ to be delivered from REX-ISOLDE following HIE-ISOLDE, elastic scattering studies ($\sim 10^4 \text{ s}^{-1}$; see for example, [Jep04]) and simple transfer reactions ($\sim 10^7 \text{ s}^{-1}$) can be performed using an appropriate DSSSD particle telescope positioned in the forward and backward (only, for elastic scattering) directions of a thin, solid target. Sufficient statistics could be obtained for an elastic scattering study in a period of about 48 hours. Transfer reactions would take a longer period of time depending upon various parameters.

Anomalous pre-solar grain elemental ratios

Pre-solar grains are ‘starry messengers’ whose chemical and isotopic composition gives information on stellar conditions under which they were produced. Recent studies of such grains have indicated very high rates of $^{30}\text{Si}/^{28}\text{Si}$. Such high rates may result for ONe novae and not CO novae. Theoretical estimates have explored the dependence of this ratio on different parameters and have deduced that it depends critically on the $^{30}\text{P}(p,\gamma)^{31}\text{S}$ reaction as does the abundance of the elements in the S–Ca region [Jos01]. The rate of this reaction has not been measured experimentally and theoretical estimates do not seem reliable. In addition, this reaction is also important for determining the reaction pathway to the production of heavier elements in a nova explosion as well as the endpoint of the rp process.

Direct measurement of the rate of this reaction is difficult due to the lack of a phosphorus beam from an ISOL facility. It is not clear if this reaction is dominated by a direct capture or a resonance process although there are low-energy resonance states that are available for the

reaction. Therefore indirect approaches may be required. For example, use of the peripheral proton transfer method, the Asymptotic Normalization Coefficients (ANC) approach [see for example, Muk06] can help elucidate a direct capture process while transfer reactions would help with deducing the energy of resonance states and level parameters (spin, widths, etc.). An ANC study could be done with an exotic beam of ^{30}P through a (^3He , d) reaction or with a ^{11}C beam through a $^{32}\text{S}(^{11}\text{C}, ^{12}\text{C})^{31}\text{S}$ proton transfer reaction at 10 MeV/u and with an intensity of the order of 1 nA. These operational parameters, while not available now, should be possible with HIE-ISOLDE.

Explosive stellar scenario and γ -ray observations

Another reaction of interest with a bearing on explosive scenarios and astronomical observations of γ -ray emission using space borne telescopes is $^{22}\text{Mg}(p,\gamma)^{23}\text{Al}$. As mentioned above, the reaction path followed in an explosive scenario can either be limited to smaller reaction networks or more forcefully pass from the CNO cycle into the rp-process path and proceed towards an end point close to $A = 100$. Observation by the Tolola Nova Survey (Williams *et al.*) and by photometry studies by the International Ultraviolet Satellite (IUE) suggest that the cores of the white dwarfs involved in nova explosions consist to a large extent of CO and ONeMg. A special subclass of about 1/3 of the observed novae shows strong optical emission lines in Ne, Na, Al and Mg. These so-called Ne-novae are believed to be an important source for galactic ^{22}Na and ^{26}Al . The latter case was already mentioned above. It should be noted that ^{22}Na and ^{26}Al are two unique signatures for reactions below mass 44 since they are the only isotopes with half-lives longer than the second range in this mass region.

The production of ^{22}Na depends on several reactions. The particular interest in relation to novae outbursts comes from attempts to observe the 1274 keV γ -ray in ^{22}Ne that follows the decay (half-life 2.6 years) of ^{22}Na after freeze out. In 1995 12 Ne-novae were studied by the COMPTEL satellite in order to find evidence for this emission from Ne-novae. However, at that time no such γ -ray emission could be observed. Later re-evaluations of the sensitivity of the observation indicated that a non-observation could be in line with predictions, although at the time this was not believed to be the case. As mentioned above, one of the objectives of the currently active INTEGRAL mission is to revisit γ -ray emission of this kind. Secondly, when the break-out from the CNO cycle occurs and the reactions proceed towards heavier masses it is important to know the reaction impedances in this region as they will determine how the flow will evolve in general. In particular, the mass of these isotopes is still low enough for the level density to be such that individual resonances may be of importance. In order to fully model the reaction network it is, therefore, of importance to study the properties of possible by-pass reactions that would reduce the amount of ^{22}Na present at freeze out. One of these reactions is clearly $^{22}\text{Mg}(p,\gamma)^{23}\text{Al}$.

Until now, there has been no direct or indirect study of capture onto ^{22}Mg . It is generally believed that ^{22}Mg would quickly enter into equilibrium with photodisintegration of ^{23}Al as the proton separation energy of ^{23}Al is only 125 keV. Nevertheless, determining the reaction rate would finally settle this matter. The reaction rate is strongly dependent on the ground-state wave function of ^{23}Al . It is currently not known if this state is dominated by a proton in the $s_{1/2}$ or $d_{5/2}$ orbital. Calculations have been performed using an extrapolated optical potential to determine the differential cross-section. As a corollary, the calculated cross-section for the $d_{5/2}$ case is generally a factor of 10 larger at its peak than for the $s_{1/2}$ case. This is consistent with the observed reaction cross-section for ^{26}Al on ^{12}C producing ^{23}Al as previously observed [Cai02]. It is suggested that this reaction be studied in two steps. In the first experiments the optical potential for proton scattering will be determined and used for

calculating the cross-section for transfer reactions. Typically, a thin plastic target will be used. Proton resonances will then be searched for, using inelastic scattering on a CH₄ gas target. Intensities needed are 1000 to 10 000 pps of ²²Mg on target. A beam energy of at least 5 MeV/u will be required in order to determine the optical potential in the energy range of interest. In the second part of the experiment the capture of a proton onto ²²Mg will be studied using an indirect method, namely, the ANC approach. As mentioned earlier, the direct capture cross-section at zero temperature can be deduced. A preferred scenario is one with a transfer from ¹⁰B or possibly ³He in order to determine the differential cross-section.

In conjunction with a recoil separator it is also possible to directly measure the transfer probability. Owing to the large difference in transfer cross-sections mentioned above, the composition of the ground-state wave function of ²³Al can be inferred. For the transfer reactions an approximate production rate of $\sim 10^7$ pps is required in order to have ~ 0.25 events/s for the ²²Mg case. It should be noted that this cross-section will be completely known after the optical potential has been determined from scattering. Similar reaction rates can also be expected for studies of the direct capture on ²³Mg, and ²¹Na.

Cycle breakout reactions

The CNO cycle provides efficient pathways to burn hydrogen to helium at high temperatures and densities. However, at sufficiently high temperatures and densities, breakout from the cycle occurs whereby carbon, oxygen and nitrogen nuclei are converted to heavier nuclei as high as $A = 100$. Breakout reactions include both radiative alpha capture and (α, p) reactions such as ¹⁴O (α, p) ¹⁷F and ¹⁸Ne (α, p) ²¹Na. The latter reaction will be described here but a similar discussion and experimental systems could also be presented for other (α, p) and (p, α) reactions. Some of these reactions are shown in Figure 2.10.

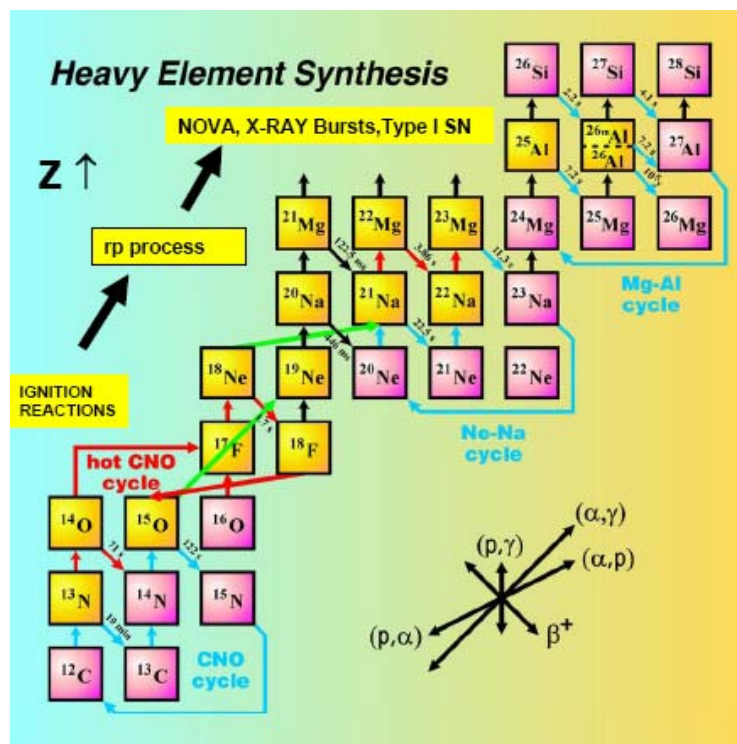


Figure 2.10: Nuclear reaction pathways and cycles that can lead to the rp process

The key unknown energy range in the centre-of-mass ($\alpha + ^{18}\text{Ne}$) system is below 2.5 MeV for this possible CNO breakout reaction, as information exists at higher energies. It is known that

there are a large number of states from the alpha threshold of 8139 keV to the studies performed previously above $\sim 10\ 500$ keV at Louvain-la-Neuve. In these earlier studies it was shown that the ^{18}Ne is processed to ^{21}Na rather than beta decaying to ^{18}F , at a density of $\sim 10^6$ g cm^{-3} and a $T_9 \sim 1\text{--}2$ K. If there are states below $E_{c.m.} = 2.5$ MeV that play a role (relatively strong resonance strength), this processing would happen at lower density/temperature conditions. This affects the pathway to heavier mass nuclei in the rp process.

The present proposed study could mimic previous studies which involved an experimental chamber containing arrays of DSSSD telescopes mounted upstream and downstream of a small He gas cell. The configuration of this facility can be similar to that used at ISOLDE or at the TUDA facility at the ISAC laboratory. It is important that the final detector configuration mask eliminate background protons from $^{18}\text{Ne}(p,p')$, although below 2 A MeV they may not be a significant problem. Beam energies range from 1.0 A MeV to 3.0 A MeV. Depending upon the final efficiency of the detection system, it is not unreasonable to assume that a resonance strength of ~ 10 eV could be measured in a period of about 50 hours with a ^{18}Ne beam intensity of $\sim 10^8$ s^{-1} , an intensity achievable with HIE-ISOLDE.

2.5.2 The s process

Neutron capture reactions are the basic mechanism for the formation of the heavy elements, which originate either from the He burning zones in asymptotic giant branch (AGB) stars or from explosive nucleosynthesis scenarios related to supernovae or neutron star mergers. For the quantitative description of the produced AGB abundances, neutron capture cross-sections are the key ingredients in the respective stellar model calculations. While a comparably solid body of data exists for the stable isotopes, experimental information for the important unstable isotopes is almost completely missing. Cross-sections for unstable isotopes are, for example, crucial for the analysis of branchings in the reaction path of the s process, which represent the major tools for obtaining independent constraints on the physical conditions of the deep stellar interior.

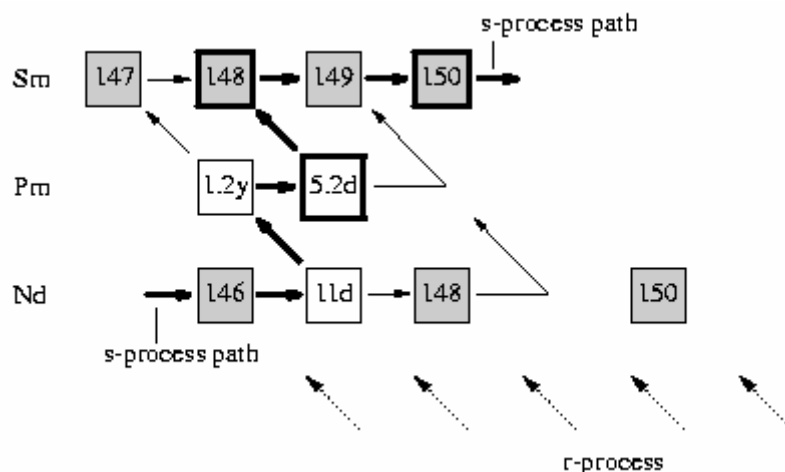


Figure 2.11: The s-process path between Nd and Sm partly bypasses ^{148}Sm owing to the branchings at $A=147/148$. The second s-only isotope ^{150}Sm experiences the full reaction flow. Note that both s-only isotopes are shielded against the respective r-process contributions by their stable isobars in Nd. The half-lives of the branching points reflect the stellar values [Tak87].

In general, the mass region of the rare earth elements is rich in significant branchings in the s process reaction chain, which have been shown to contain a wealth of information concerning

the neutron flux, temperature, pressure, and mixing mechanism during the *s* process. Branchings are local phenomena as indicated in Figure 2.11 at the examples around $A = 147/148$. The strength of a branching can be expressed in terms of the rates for beta decay and neutron capture of the unstable branch point nuclei as well as by the σN_s values of the involved *s*-only isotopes ^{148}Sm and ^{150}Sm which stand for the corresponding parts of the reaction flow. Since the effect of the branching on the *s*-only nuclei is often small (e.g., 10% in Figure 2.12), all cross-sections, including those of the unstable branch point isotopes, have to be determined with an accuracy much better than can be obtained by theoretical calculations.

The approach in these studies is based on the use of the production of sufficiently thick targets of implanted radioactive isotopes which can then be used for *n*_TOF studies.

Based on the neutron capture cross-section measurement on the unstable isotope ^{151}Sm which has been performed by the *n*_TOF collaboration [Abb04, Mar06] and on the improved neutron flux and backgrounds expected at the proposed second experimental area (EAR-2) of the *n*_TOF facility, the sensitivity for measurements on small, unstable samples can be expressed by a figure of merit of

$$m \cdot \sigma / A = 20 \mu\text{g mbarn}$$

where m is the minimal sample mass in μg , σ the expected stellar cross-section in mbarn, and A the atomic mass [Men05]. For an average cross-section of 100 mbarn and assuming an isotope in the mass range around 150, this implies a minimal sample mass of 3 μg or 10^{16} atoms. That measurements can be performed on very small samples of a few μg is the result of the excellent performance of the *n*_TOF facility, which is particularly suited for such applications because of the unique luminosity of this neutron source.

However, the production of pure samples of this size is currently the main obstacle to experimental studies of the respective neutron capture cross-sections. The most promising way of obtaining the necessary isotopic and chemical purity appears to be the high intensities of future radioactive beam facilities such as HIE-ISOLDE. Using these beams for implantation into ultra-pure carbon foils could probably be done in parasitic mode and would accumulate the necessary sample mass in a few days. This solution would not only couple ISOLDE and *n*_TOF closer together but would have the further advantage that production on-site would ease the problems related to the limited lifetime of these samples.

2.5.3 The *r* process

The *r* process is a pathway of rapid neutron capture reactions, thought to be the major production mechanism of most elements heavier than iron. The *r* process runs through extremely neutron-rich regions of the nuclear chart where there is little or no structural information, even though structure can have a dramatic effect on the reaction rate. There is already early evidence of quenching of shell structure around the $N = 82$ *r*-process waiting point from β -decay studies performed at ISOLDE. Solar abundance calculations for *r*-process nuclei also provide strong indirect evidence for shell quenching effects. The leakage rate of material to heavier masses can be strongly influenced by neutron-capture cross-sections. Since direct (*n*, γ) capture measurements cannot be performed on these nuclei, (*d*,*p*) reactions provide the most feasible route for determining this information — cross-sections have been shown to vary by a factor of ~ 1000 depending on the structural information assumed for *n*-rich Sn isotopes. Modelling the process therefore relies on extrapolation of nuclear-structure models developed nearer stability. Experimental single-particle strengths around closed shells provide much of the basic input for these; studies of doubly-magic nuclei plus/minus one nucleon are especially relevant for tests of large-scale shell models. In particular, *quantitative*

measurements of single-particle states around the ^{132}Sn core would help constrain these models in a wide range of heavy nuclei. Studies of the (d,p) reaction will give more definitive assignments of spins to the states and their single-particle nature will be quantified, for the first time, through measurements of spectroscopic factors.

2.5.4 General experimental techniques

Mass measurements

Mass measurements are extremely important for providing a realistic guide to the development of accurate theoretical approaches to the calculation of masses near to the dripline. It has been shown on many occasions that mass model predictions quickly lose any degree of predictive capability as one departs from stability. Such calculations are very important for many applications and, in particular, for understanding mechanisms of reaction pathways involving very exotic nuclei, e.g. the r process for the production of elements heavier than iron (see Figure 2.12). In addition, the rates of nuclear reactions depend exponentially on the reaction Q -value, so mass measurements play a crucial role as a first step towards providing an estimate of these reaction rates.

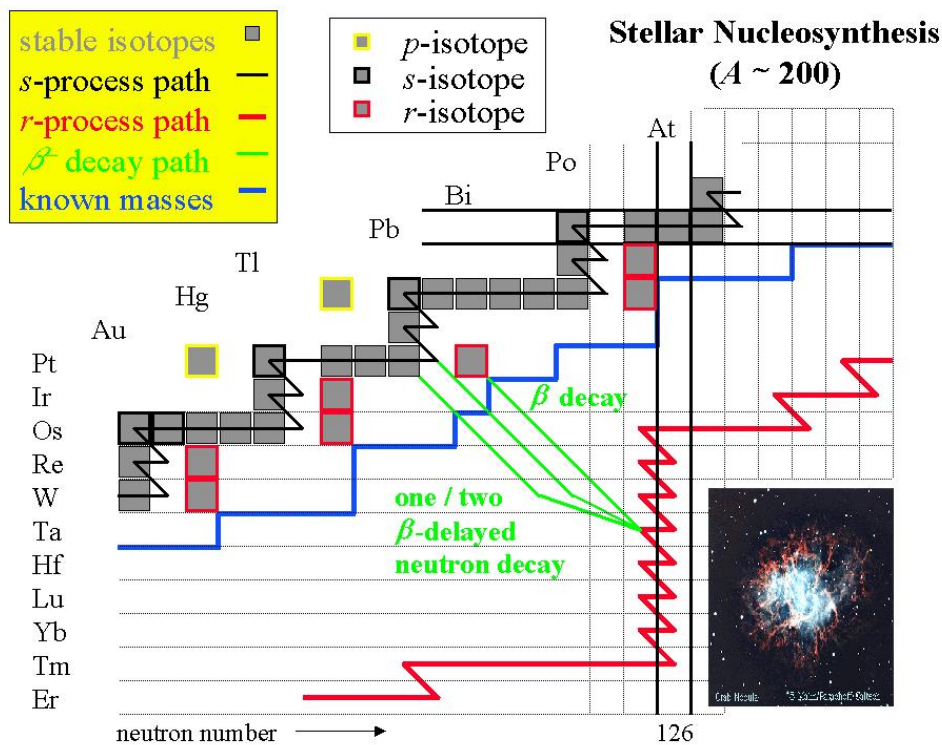


Figure 2.12: Area of the nuclear chart around $A=200$ showing possible s- and r-process paths. Also shown is the area of known masses illustrating the need for reliable model predictions.

In the last few years, the ISOLTRAP mass spectrometer has performed mass measurements on more than 300 different nuclides, with many masses determined for the first time, especially for neutron-rich isotopes. HIE ISOLDE will provide beams of higher intensity and a higher degree of reliability. This will allow the study of nuclides which are further from the valley of stability, where the current production yields are too low for mass measurements, (e.g., for MISTRAL and ISOLTRAP a few hundred ions/s are required). In addition, it is planned to work with highly charged ions, provided by charge breeding devices like an EBIS (electron beam ion source) or an ECR ion source. This will also help to reach a higher

accuracy and to measure trapped nuclides with half-lives of less than 10 ms. Therefore, the long and pioneering tradition of performing mass measurements at ISOLDE can continue.

The regions of special interest for nuclear astrophysics are masses at or near the $A = 80$ and 130 r -abundance peaks, or specifically around $N = 50, 82$ and $N = 126$; and masses ‘in the r process’ in the shape-transition regions; i.e., around $N = 70$ (e.g., ^{110}Zr etc.), $N = 88$ (e.g., ^{140}Tl etc.), $N = 110$ (e.g., ^{172}Sm etc). The pathway of the r process is crucial to our understanding of the production of most elements heavier than the Fe region and such measurements will play an important role in clarifying these questions.

A second major area of interest is the rp process and specifically additional information on the pathway in the medium mass region, and at the end-point. This process follows the proton dripline and mass measurements are needed particularly in the region above $A = 35$ to the Sn region ($A = 100$).

Decay scheme studies

Related to mass measurements there is an urgent need for classic decay scheme studies in the same mass regions as mentioned above. Half-lives for beta decay can be long compared to reaction rates, and then play a significant role in determining the exact pathway. Waiting point nuclides do affect final abundances as a result of such long half-lives.

Aside from standard gamma, beta, and alpha spectroscopy studies as have been performed at ISOLDE over many years, additional data is required on beta-delayed neutron (BDN) emission. Such information plays a key role in understanding the abundances of the elements as it affects the pathways of both the s process and the r process. Also, coupled with data taken in related reactions studies, e.g., (d,p) reactions, BDN can help to deduce radiative neutron capture on very exotic neutron-rich nuclides, information not easily or impossible to obtain in direct measurements. Examples of such experimental studies can be found in [Dil03, Kra00].

Reaction studies

Explosive stellar scenarios involve many radioactive nuclei as reactants and it will now be possible to perform either direct or indirect studies to determine these reaction rates, previously impossible to measure. Radiative proton, neutron, and alpha capture reactions involving stable beams have been measured in the past and similar techniques can be applied with exotic reactants. Further, new approaches are also being developed. Resonant and non-resonant capture reactions must be measured either directly with clever indirect approaches such as the so-called Trojan Horse approach or the ANC method. It should be noted that resonant reactions involving narrow, well-separated resonances play an important role in reactions involving low- Z reactants, while for heavier masses some estimates of cross-sections can be obtained using statistical approaches such as the Hauser–Feshbach method. Cross-sections for capture reactions can be determined by detailed balance from inverse photodissociation reactions such as Coulomb dissociation. Particle transfer reactions such as (p,α) and (α,p) are needed not only for the direct role they play in explosive processes but also to provide a method to measure rates indirectly. Elastic scattering reactions are needed to study resonant states, especially at higher excitation energies, and from such studies we learn about the Coulomb amplitude and the nuclear amplitude. Inelastic scattering can tell us about the properties of states in a compound nucleus where decay by particle emission to an excited state is possible. Of course such reactions play a key role when attempting to unravel the

reaction rate of inverse processes. Multi-nucleon transfer reactions play a role also in providing information on nuclear structure of nuclei far from stability. Reactions such as (p,t), (^3He ,n), (^3He , ^6He) have proved very useful and can be performed in inverse kinematics using exotic beams. Examples of some of these studies, which could be performed at HIE-ISOLDE, are presented in Sections 2.1.2 and 3.5.

2.6 Solid-state physics with radioactive beams

Radioactive nuclei from various sources have been used for condensed matter investigations for a long time. The earliest application of radiotracers was the investigation of diffusion processes [Gro20]. Nuclei are now being routinely used as probes of their environment in metals and semiconductors via various methods. More recently, these techniques have also been applied to the study of complex bio-molecules, surfaces, and interfaces. This spin-off from nuclear physics research has been increasing steadily in scope. With the routine availability of high-purity radioactive ion beams from isotope separators the possibilities for such investigations have been greatly expanded, permitting technologically ever more demanding experiments. In particular, the use of on-line isotope separation at the CERN/ISOLDE facility has demonstrated the great potential of nuclear probes for solid-state physics research; during the last 17 years approximately 25% of the beam time has been devoted to condensed matter applications, see Figure 2.13 for an overview. If a mid-term upgrade of the ISOLDE facility is planned, it is natural to expect that applications in materials science are going to constitute an important research field there too. The future user of ISOLDE would be able to utilize the higher beam energies, qualities, and intensities available.

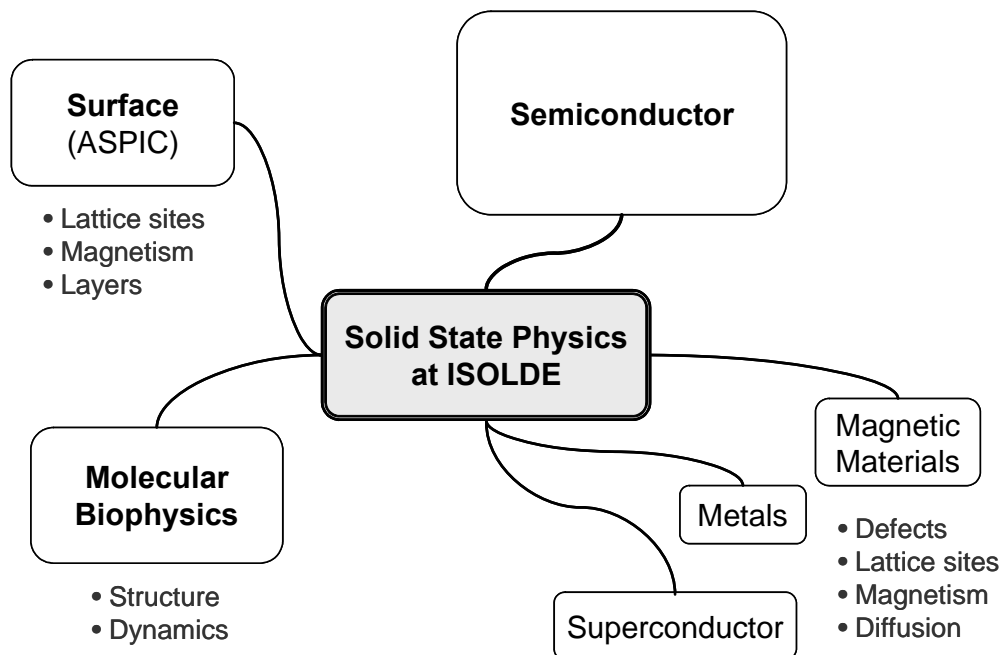


Figure 2.13: Recent research topics in solid-state physics at ISOLDE

To give an impression of the wide variety of possible applications, a short summary of the present uses of radioactive ion beams for solid-state applications is presented first, mostly from projects currently running as part of the ISOLDE programme at CERN. More detail on these projects can be found in a special volume of the journal *Hyperfine Interactions* [For00].

This is followed by a more detailed description of possible future applications of radioactive ion beams in materials science making use of a mid-term upgrade of the ISOLDE facility.

2.6.1 Currently possible experiments

Nuclear methods allow the investigation of impurities in condensed matter at very low concentrations, to the extent of essentially isolated impurity atoms. Crucial for such research is the availability of an isotope with suitable decay characteristics and half-life, but also the ‘clean’ incorporation into the material to be studied. Therefore, it is obvious that the use of the chemical techniques required to produce samples from commercially available radioactive isotopes limits the scope to a few easy cases. Further possibilities have been opened up by production of the required sources directly at reactors or accelerators. A considerable simplification was brought about by the application of on-line isotope separator implantation for sample production.

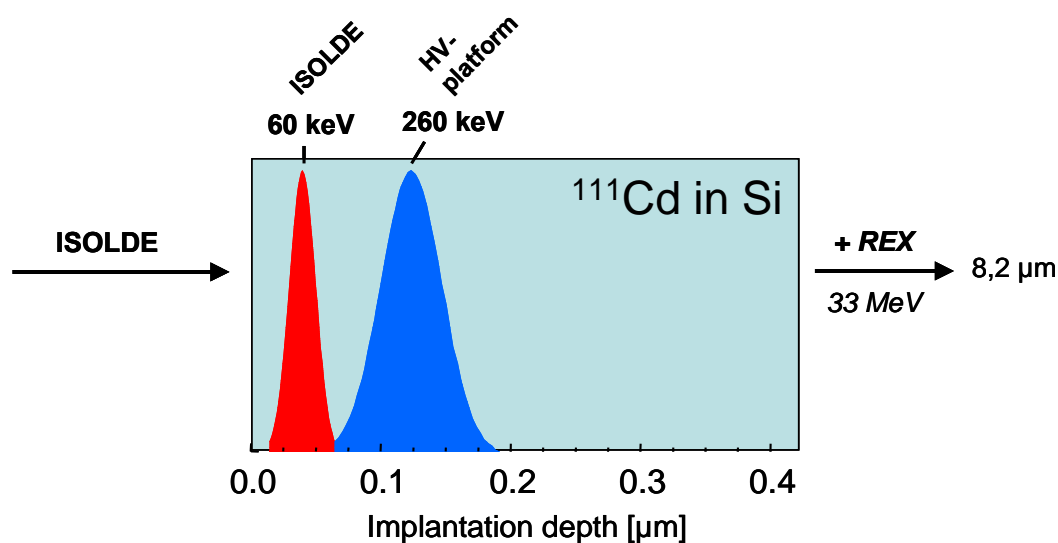


Figure 2.14: Possible implantation energies and corresponding implantation depth for ^{111}Cd in Si, today

The major step forward, however, was the use of on-line isotope separators, in particular ISOLDE. This facility has, therefore, attracted a large number of users from solid-state physics. The solid-state experiments take advantage of the wide choice of isotopes available at ISOLDE which can be implanted into the matrix under investigation with the separator energy of 60 keV. Additionally, by using a high-voltage (HV) platform as post-accelerator, implantation energies up to of 260 keV can be achieved. With REX-ISOLDE the isotopes can be accelerated to 300 keV/u yielding an implantation energy of several MeV. This high implantation energy causes an implantation depth of several μm , see Figure 2.14, which is useful only for some experiments in solid-state physics. At the moment there is a gap of implantation energies between the HV platform and REX-ISOLDE. A wide variety of experimental techniques has been introduced for the studies of the implanted samples, briefly summarized below. Many different condensed matter systems are being investigated with these nuclear techniques, in particular semiconductors, metals, surfaces, and interfaces, but also such complex materials as ceramics, high-Tc superconductors, or bio-molecules. In Figure 2.15 the elements that have isotopes used for solid-state experiments at ISOLDE are outlined.

Ia	Ila	IIla	IVa	Va	VIa	VIIa	VIIIa	Ib	IIb	IIIb	IVb	Vb	VIb	VIIb	VIIIb		
H															He		
Li	Be									B	C	N	O	F	Ne		
Na	Mg									Al	Si	P	S	Cl	Ar		
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

H	Elements produced as radioactive beams at ISOLDE	Li	used in solid state experiments
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Figure 2.15: Elements produced as radioactive beams at ISOLDE and used for solid-state experiments

Perturbed angular correlations

For the technique of perturbed angular correlations (PAC), isomeric nuclear states in the nanosecond–microsecond time window of the method are needed. These are populated in many radioactive decays, in particular those further away from the stability line. The technique, therefore, lends itself extremely well to on-line isotope separator implantation. In this way the spectrum of possible isotopes for this method could be greatly extended at ISOLDE, and the full potential has not yet been exhausted. For laboratory experiments only very few isotopes are suitable (^{111}In , ^{181}Ta , and a few more). The easy availability of short-lived sources has led to the application of about 25 different source isotopes at ISOLDE. The shortest half-life used up to now is 2 minutes, but for on-line experiments there is in principle no limit, and a few more cases with source half-lives down to seconds still wait to be exploited.

In conventional PAC two γ -rays are observed in delayed coincidence. For many decay schemes, however, the detection of the conversion electrons is more favourable. A spectrometer for electron- γ or electron–electron PAC has, therefore, been installed at ISOLDE [Cor00]. This technique, uniquely suited to implanted systems, has found promising applications in metal and semiconductor physics. The PAC experiments have concentrated first on metallic systems, in particular on the electric field gradients extracted from the nuclear quadrupole interaction. This property has then been widely exploited for investigations of semiconductors, surfaces, and bio-molecules. Recently, interesting results have been obtained on high-Tc superconductors [Cor06] and colossal magneto-resistance systems (CMR) [Ama06].

Mössbauer spectroscopy

The use of Mössbauer spectroscopy in solid-state physics is well established. One major drawback of the technique, however, is that only very few isotopes exist with suitable decay characteristics. For laboratory experiments generally very long-lived source isotopes are needed (e.g., ^{57}Co ($t_{1/2} = 272$ d), $^{119\text{m}}\text{Sn}$ ($t_{1/2} = 293$ d)). This limitation does not exist at an on-line implantation facility. The Mössbauer measurements conducted in a long series of

experiments at ISOLDE have, therefore, made use of short-lived sources such as ^{57}Mn , ^{119}Sb or ^{119}In . These have been applied very successfully in the studies of implantation behaviour in metals and semiconductors. In many cases the results have then led to further studies of the systems investigated by other nuclear techniques, such as channelling/blocking or perturbed angular correlations. Obviously the combination of different techniques has led to further insight, in particular concerning the lattice site taken up following implantation. Furthermore, Mössbauer experiments at ISOLDE were the first to demonstrate site-selective doping of compound semiconductors [Wey80].

Low-temperature nuclear orientation

The technique of nuclear orientation (NO) depends on a solid-state property, the strong magnetic fields at the nuclei in magnetically ordered solids, metals like Fe, Co, and Ni in particular. The on-line facility NICOLE at ISOLDE routinely makes use of these fields for nuclear spectroscopy studies. Though much of the required solid-state information is by now well known, and also reasonably well understood, some interesting details are still emerging. Careful experiments with sources from ISOLDE have recently led to a systematic study of spin-orbit-produced electric field gradients in cubic metals, and the first steps towards a quantitative understanding of this phenomenon [See01].

Decay labelling

For the physics of semiconductors and, therefore, also for their technological application, it is vital to have as much information as possible on the properties of impurity atoms. Various electrical or spectroscopic techniques are routinely used to investigate such problems. One of the major difficulties of these conventional methods is the assignment of an observed signal to a specific impurity element. This is by no means trivial, since the intentionally introduced impurities might be masked by defects or other impurities. It is here that the use of radioactive dopants can be of decisive advantage. With the radioactive decay, certain signals can disappear or appear and thus be directly assigned to the incorporated radioactive element. Methods where this approach has been successfully applied at ISOLDE include the Hall effect, photoluminescence (PL), deep-level transient spectroscopy (DLTS), and electron spin resonance (ESR). Recently, a state-of-the-art PL laboratory, called APRIL, has been set up near the ISOLDE hall to enable PL experiments with such short-lived isotopes. Thus isotopes with quite short half-life [^{64}Cu ($t_{1/2} = 12.7$ h) and ^{65}Ni ($t_{1/2} = 2.5$ h)] could also be successfully employed [Agn06].

Diffusion studies

Diffusion of atoms in solids is a fundamental process in condensed matter that has been investigated in great detail. Obviously the first studies concentrated on the self-diffusion of the matrix atoms. Here the marking of the diffusing atom by its decay properties is the most convenient way to follow the depth distribution. Such tracer diffusion studies are also most suitable for investigating the diffusion of impurity atoms, and absolutely essential for systems with low solubility.

Experiments at ISOLDE first concentrated on impurity diffusion in simple metals, later on semiconductors, and finally on complex ceramic materials. For depth profiling different conventional techniques were first employed, followed later by an on-line apparatus using sputtering [Str02]. Thus, isotopes with quite short half-life [^{11}C ($t_{1/2} = 20$ min) and ^{31}Si ($t_{1/2} = 2.6$ h)] could also be successfully employed [Vos02].

Channelling/blocking

The technique of determining sites of impurity atoms in crystalline solids by measuring the channelling/blocking pattern of the emitted radiation from single crystals lends itself perfectly to isotope-separator-produced samples. The typical implantation depth of some 10 nm is just what is required in most cases. The technique also puts no stringent conditions on the decay properties. Charged particles to be used can be α - or β -particles or conversion electrons. Generally, a small source spot is required which can be obtained with little difficulty by focusing the ion beam.

At ISOLDE channelling/blocking has been used extensively in the localization of impurity atoms implanted into semiconductors, but also in some metals. While first experiments were conducted with single detectors, a major improvement was achieved with the use of 2-dimensional position-sensitive devices [Wah98].

2.6.2 Future possibilities at an upgraded ISOLDE facility

Most of the experimental programme in solid-state physics running at present has a long-term perspective. It might therefore be envisaged that similar projects would also be launched in this area at an upgraded ISOLDE facility. Obviously the higher intensities of the low-energy beams to be available there can facilitate such projects and also possibly widen their scope. Such possible uses will not be considered further here, since they will naturally be follow-ups of the projects currently running at ISOLDE.

There exist several other possible future applications of radioactive ion beams that would be highly interesting, but cannot be performed at the present ISOLDE facility for various technical reasons. New high-purity isotope beams will, as they have done in the past, also open up new applications in solid-state physics. Since such developments are within the scope of the ongoing ion source improvement research, they will also not be elaborated upon here. There are, however, three important features of the ion beams of the mid-term upgrading:

- a. Higher beam energy
- b. Higher beam quality
- c. Higher beam intensity

Possible projects that would need these features for condensed matter applications are described in detail below.

Deep-level transient spectroscopy

The higher beam energies available at ISOLDE will also open up new perspectives for several measurements performed on semiconductors. The deeper implantation will permit the use of even smaller impurity concentrations than are possible at present. By varying the energy of the ions in the 0.1 to 10 MeV range, homogeneous depth profiles can be produced with a much lower dopant concentration. The deeper implantation will also help to avoid the sometimes troublesome influence of surface defects and space charge effects.

Clearly the most appealing possibility is the deposition of the radioactive ions at a well-specified depth. This would allow us to reach a specific layer in multi-layered structures, so

important in modern device technology. One experiment that could especially profit from this possibility is the technique of deep-level transient spectroscopy (DLTS).

In a DLTS experiment the capacitance change of a diode at different times after voltage switching is measured at variable temperature. Deep energy levels in the bandgap of the semiconductor, generally due to impurities or defects, are then thermally populated and depopulated at the different bias voltages. However, only levels of atoms at a certain distance from the diode interface contribute to the effect. Typically, this depth is of the order of 500 nm, but it can vary widely as a function of the electric properties of the semiconductor.

At present it is, of course, not possible to implant the radioactive atoms to be studied directly into the specific depth. The DLTS experiments performed to date at ISOLDE [Pet90], therefore, had to resort to diffusion steps to bring the impurities to the required depth. Such thermal diffusion is generally not possible with a complete diode structure, so that the production of the interface had to be done after the thermal diffusion. This complication has greatly restricted the application of DLTS with radioactive atoms, and thus the decay labelling of the observed levels to a specific element.

In a recent experiment, the possibility of using REX-ISOLDE for implanting the radioactive atoms into a specific depth was tested. Since the energy of the radioactive beam of REX-ISOLDE is (at 300keV/u) too high for the implantation depth needed, the beam needs to be decelerated by passing it through a carbon foil of the right thickness. In addition we are going to add the possibility of tilting the foil against the beam direction to change the effective thickness.

The first experiment in 2002 using the radioactive isotope ^{153}Sm implanted in p-type 6H-SiC was a partial success. The analysis of the DLTS data shows the decay effects of one deep level in the sample caused by the decaying ^{153}Sm . The setup with the carbon foil as decelerator leads, however, to irreproducible implantation energies. Thus, the signal from the DLTS experiment cannot be assigned correctly to an electronic level.

Further experiments of ^{156}Eu (IS416) scheduled in May 2004 failed owing to a very low yield. Not even a part of a pA of the 28+ charged ions was measurable on the target at the second beam line of REX-ISOLDE. The tiltable carbon-deceleration-foil together with a silicon-detector was intended to control and adjust the exact beam energy. The yield of the REX facility has to be improved for further collections with the proposed technique. Best collections for the proposed DLTS experiments on (neutron rich) rare earth isotopes might be possible with a HV setup accessible with highly charged ions. Energies in the range of 1–6 MeV per ion and a current of at least a few 10 pA, achievable with the proposed ECR setup would be perfect for radiotracer DLTS investigations of a large variety of wide bandgap semiconductors. A depth-homogeneous concentration of dopants could be achieved with a tuneable implantation energy by applying a SRIM-simulated energy-dose-programme. Applying the mentioned half-life sensitive radiotracer DLTS, it is acceptable to have a beam contamination of oxides and isobaric isotopes of the same order of magnitude as the isotope to be investigated, if these contaminations have half-lives far from that of the desired isotope.

Local regrowth studies of voluntarily induced damage on optoelectronic materials

In most optoelectronic materials the annealing of damage created by ion implantation within a few hundred nanometers, at the near surface region, has been carefully studied. Quite recent

studies, aiming to tune the refraction index of lithium niobate, have been performed using very low doses, 10^{10} – 10^{13} ions/cm², of heavy ions with energies between 5 and 30 MeV. In this energy range, damage is created in thick layers that can reach 3 to 10 micrometers. Yet, the damage introduced with such low doses is enough to significantly change the refraction index of LiNbO₃.

Micromachining the interface between implanted and non-implanted regions with ion implantation and annealing led to the formation of a regular modulation in the crystal surface that has been observed with an optical microscope and characterized by AFM. With the present proposal we aim to use very high-energy stable and radioactive beams to extend these studies to a higher energy range of implantations. By overlapping two (or more) very thin single crystals of LiNbO₃, the highly energetic stable ions will create damage only in the first crystals, on account of the electronic stopping power. In the last crystal both nuclear and electronic damage will be created. Each crystal will now be implanted at selected depths with lower doses of still energetic radioactive nuclei which are suitable for hyperfine interactions studies using the PAC technique. In this way we aim to follow the reorganization of the damage, layer by layer, and study the basic mechanisms of the annealing.

Diffusion in highly immiscible systems

Diffusion studies with the conventional radioactive tracer technique, whether they are followed up by sectioning of the sample or by some sort of depth sensitive radiation counting, require a certain solubility of the diffusing element for the development of the characteristic diffusion profile. In cases where strong forces keep the impurity atoms at the sample surface, these methods are not applicable. It is here that deep implantation of high-energy radioactive ion beams could find a very interesting and unique application.

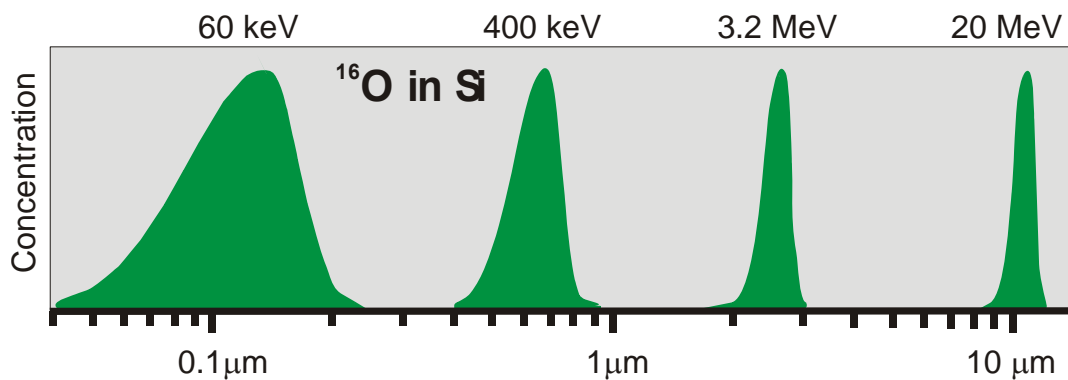


Figure 2.16: Typical range profiles for implantation into solids at various energies. We can expect that a well-defined depth of the order of a few μm can be obtained at typically 100 keV/u.

Typical implantation profiles for a wide range of implantation energies are shown schematically in Figure 2.16. It may be noted that the degree of localization in a predetermined depth improves with energy on a relative scale, even though the absolute width of the range distribution due to straggling naturally grows with energy. The system of isolated impurity atoms at a specific depth lends itself perfectly to the investigation of diffusion even for completely immiscible systems. Such systems produced by forced alloying are of increasing technological importance. Their systematic study at high implantation depth and very low concentration could lead to a better understanding of the processes occurring in the materials with practical applications.

Beta-NMR with tilted-foil polarization

Beams of polarized radioactive nuclei open the possibility for interesting applications in various fields. In addition to possible uses in nuclear beta decay studies, such beams would be well suited for β -NMR experiments with short-lived isotopes. The combination of a radioactive ion beam facility with the tilted-multifoil method would allow the production of such nuclei, their subsequent polarization and then measurement of the hyperfine interaction of the nuclear moments with the fields of their surroundings using the β -NMR technique. The tilted-foil polarization technique discussed here that can be implemented at HIE-ISOLDE is also discussed in Section 3.3.1, the alternative method of optical pumping in an ion trap is mentioned in Section 3.2.3.

If an ion beam is passed through a very thin foil, tilted with respect to the beam direction at an oblique angle, the electronic states of the outgoing ions are polarized. Polarization is initially introduced in the orbital motion of the electrons by the surface interaction on exit of the ion from the foil. During flight in vacuum some of this electron polarization (which is in the direction $\mathbf{n} \cdot \mathbf{v}$, where \mathbf{n} is the unit vector perpendicular to the surface of the foil and \mathbf{v} is the ion velocity vector) is transferred via hyperfine interaction to the nucleus. By successive passage of several such foils, interspaced with regions of free flight to allow a significant nuclear precession around the total angular momentum $\mathbf{F} = \mathbf{I} + \mathbf{J}$ in flight, the effect can be enhanced. The expectation is that rather sizeable nuclear polarizations can be achieved for a wide variety of elements.

The tilted-foil mechanism has already been used to induce in-beam polarization of nuclei at the several per cent levels [Rog86]. It has also been applied for the measurement of signs of quadrupole moments of high-spin isomers [Daf85] and of parity violation in the $17/2^-$ isomer of ^{93}Tc [Bro90], again a high-spin state. In those experiments the ion velocity was generally in the range of 0.01 c to 0.03 c . Conditions relevant to experiments at a radioactive beam facility differ substantially from these earlier experiments. Nuclei of generally lower nuclear spin \mathbf{I} are used, requiring only a small number of foils. A lower ion energy in the range of 50 to 100 keV/u should lead to a larger polarization, though this expectation has not been verified by experiments to date. The smaller size, angular divergence, and energy spread of the radioactive beam, combined with the typically higher count rates, can also make the experiments easier.

In a pilot experiment at ISOLDE, making use of a high-voltage platform [Haa97] for a moderate post-acceleration of the ion beam, the feasibility of the proposed experimental project has been demonstrated, and the magnetic moment of the nucleus ^{23}Mg was measured [Lin97].

The relatively simple experimental setup is sketched in Figure 2.17. The polarized ions are stopped in a crystal, generally cooled to low temperature in order to increase the spin-lattice relaxation time. A holding magnetic field, best produced by a superconducting magnet, is also applied parallel to the polarization direction. For radioactive nuclei the polarization is most conveniently determined by measuring the angular distribution of the emitted β particles. It has the form $W(\theta) = 1 + B_1 A_1 \cos(\theta)$, where θ is the angle with respect to the polarization direction. An RF field is applied to the stopped polarized nuclei and tuned until the polarization (and hence the β -asymmetry) is destroyed. The frequency of this NMR resonance can be measured with high precision.

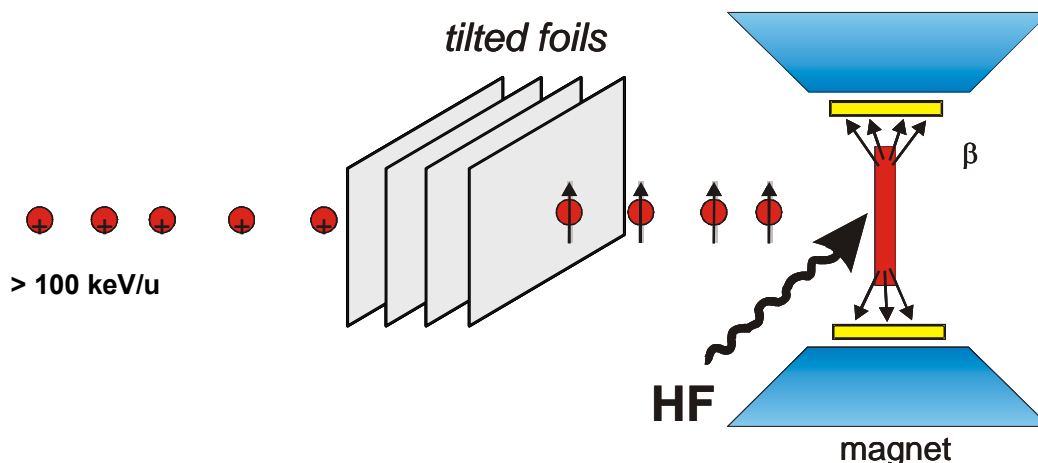


Figure 2.17: Schematic representation of the β -NMR set-up using the multifoil polarization technique

Beta-NMR has the potential to become a very powerful tool for the investigation of condensed matter. It would complement the other nuclear probe techniques generally used at a radioactive beam facility for studies of the environment of implanted nuclei in solids. Until now only a few probe nuclei have been useful for this method, owing to the difficulty of producing polarized nuclei. The only technique that is potentially universal employs the capture of polarized neutrons. Experiments on ^8Li , ^{11}B , ^{20}F and a few others have been successful [Ack85]. The usefulness of this technique for solid-state applications, however, is seriously limited by the fact that the samples have to contain a large amount of the element to be studied, thus preventing the investigation of dilute impurities, otherwise characteristic for the nuclear methods. The exceptions are ^{12}N and ^{12}B , the only nuclei suitably polarized following nuclear reactions [Min83] and ^8Li , which have been used for β -NMR following laser-polarization at ISOLDE [Itt99]. Nevertheless, the few applications of the β -NMR method have demonstrated the power of NMR coupled to nuclear detection. Pioneering studies of nuclear relaxation, diffusion, radiation defects, and glass structure have been performed.

With the development of the tilted-foil technique the possibility of obtaining polarized ion beams will open up the wide spectrum of isotopes available at ISOLDE for applications of β -NMR spectroscopy. Clearly, the strength of the method lies with the lighter elements, where spin-lattice relaxation times are sufficiently long for investigations over a wider temperature range. For these technologically important implants generally no probe atoms suitable for the other nuclear methods like MS or PAC are available. It is difficult, however, to predict which isotopes will be most suitable for condensed matter studies. Exploratory measurements of the β -asymmetries for several of the most interesting cases are necessary before one can discuss in detail a solid-state research programme with the new technique. Measurements of the spin-lattice relaxation or Knight shift for light impurities in metals are still very scarce. Together with the hyperfine fields in the few simple ferromagnets, they would give direct information on the conduction electron density at the impurity site, one of the few ways to test band structure calculations on a microscopic scale.

The elements of the first two periods are especially important as dopants and impurities in currently used semiconductors, and even more so in diamond and SiC, the semiconductors of the future [Gla90]. Beta-NMR could give direct information about electronic and lattice structure, especially as the nuclear quadrupole interaction can also be measured with NMR accuracy. The further development of radioactive beams of the reactive light elements (B, C,

N, O, and Al, Si, P, S) will be of great significance in this respect. Several of the mirror decays (^{11}C , ^{13}N , ^{27}Si) should be very suitable for the new technique.

As a representative example of an actual experiment one could consider the investigation of implantation of C and Si into the various forms of SiC by way of the electric field gradients acting on the probe nuclei of ^{11}C and ^{27}Si . For both elements there exists no stable isotope that would allow the measurement of nuclear quadrupole coupling constants. Therefore, one would first test the technique by implantation into non-cubic solids such as graphite. Then a series of measurements of the β -NMR pattern at different temperatures could be performed and interpreted to determine the defect configurations present. Later, a series of double resonance experiments with the stable nuclei of the matrix could give further details on the lattice site taken up after implantation. For example, silicon atoms occupying carbon sites (antisite defects) will show a stronger coupling to the matrix Si spin system than the substitutional atoms. One would probably also investigate a few samples with different doping levels to detect the influence of charged lattice defects. Such a programme could typically run for 2–5 years, depending on the suitability of the probe nuclei chosen and the significance of the initial results. The required beam energies are in the order of 100 keV/u; however, with a large uncertainty in the present expectations. Various test runs to find the optimal conditions for the solid-state experiments would certainly have to be made. Intensities of 10^7 ions per second should be largely sufficient.

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3 Experimental methods and requirements

3.1 Mass measurements

3.1.1 Precision mass spectrometry of short-lived nuclides

High-precision mass values and hence binding energies and Q -values of radioactive nuclides allow important tests of symmetry concepts in nuclear physics and searches of physics beyond the Standard Model (SM) of particle interaction to be made [Lun03]. Examples are: tests of isospin symmetry through the very precise mass predictions of the isobaric-multiplet mass equation IMME; the search for scalar currents that are not predicted in the conventional SM by precision beta-neutrino correlation experiments; and a test of the conserved-vector-current hypothesis, a postulate of the SM. In addition, masses of short-lived radionuclides are important for nuclear structure studies, for testing mass models far from stability, and for reliable nucleosynthesis calculations in astrophysics. The relative mass accuracy needed in several of these cases is 10^{-8} or even below, with direct mass measurements only achievable with Penning traps.

At the ISOLDE facility there are two main approaches to perform mass measurements of exotic nuclei, namely using the ISOLTRAP (Penning ion trap) system [Bla05] or using the MISTRAL (RF, transmission spectrometer) approach. Both experimental set-ups have been described in previous reports (see, for example, [Lun03]). While ISOLTRAP allows very accurate mass measurements with a relative mass uncertainty down to $\delta m/m = 8 \times 10^{-9}$, the MISTRAL spectrometer can access very short-lived nuclei with half-lives of only a few ms (with a relative mass uncertainty of 10^{-7}). Of course, mass estimates can also be made using traditional spectroscopic approaches, e.g., through beta decay and reactions. While less accurate, sometimes they are the only method for the most exotic species.

Ion traps play an important role not only in high-precision experiments on stable particles but also on exotic nuclei. Besides accurate mass measurements they have recently been introduced to nuclear decay studies and laser spectroscopy as well as to tailoring the properties of radioactive ion beams [Klu03]. This broad usage of trapping devices at accelerator facilities is based on the manifold advantages of a three-dimensional ion confinement in well controlled fields: first, the extended observation time is limited only by the half-life of the radionuclide of interest. Second, the ion beam performance can be improved by ion accumulation and bunching, for example, which allows an efficient use of rare species. Third, stored ions can be cooled and manipulated in various ways; even charge breeding of the ions, as performed, for example, in REX-EBIS.

For on-line mass measurements on short-lived radionuclides the ISOLTRAP Penning trap mass spectrometer installed at ISOLDE/CERN plays a prominent role. Atomic masses are determined with an uncertainty of 10^{-8} for nuclides that are produced with yields as low as a few 100 ions/s and at half-lives well below 100 ms.

At ISOLTRAP the mass measurement is carried out via the determination of the cyclotron frequency

$$\nu_c = qB/(2\pi m) \quad (1)$$

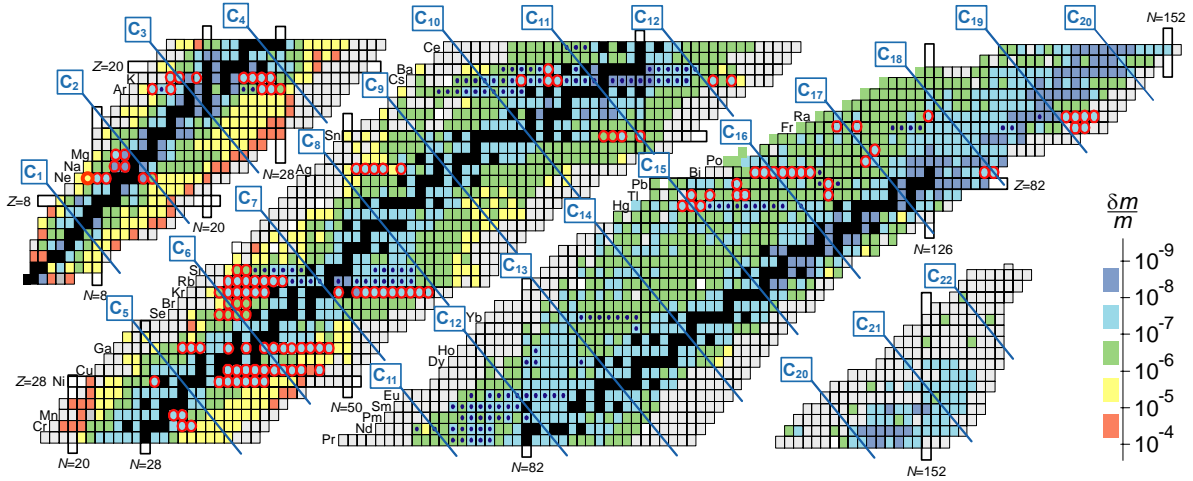


Figure 3.1: Nuclear chart with the relative mass uncertainties $\delta m/m$ of all known nuclides shown in a colour code (see scale bottom right, stable nuclides are marked in black). Masses of grey-shaded nuclides are estimated from systematic trends [Aud03]. Masses measured with ISOLTRAP since 2002 are marked with red circles, earlier measurements with blue dots. The isobaric lines of the carbon clusters C_1 to C_{22} demonstrate the advantage of using a ‘carbon cluster mass grid’ for calibration purposes.

of an ion with a charge-to-mass ratio q/m confined in a strong magnetic field with magnitude B . The magnetic field strength is obtained from the cyclotron frequency $\nu_{c,\text{ref}}$ of a well-known reference mass (ideally ^{12}C since the unified atomic mass unit is by definition 1/12 of the mass of that nuclide, see Figure 3.1). For beam purification and subsequent mass measurements ISOLTRAP uses two Penning traps placed in superconducting magnets of 4.7 and 5.9 T field strength, respectively, with a field inhomogeneity of 10^{-7} – 10^{-8} in the precision trap [Bla03]. For the determination of the cyclotron frequency, i.e., the actual mass determination of the confined ions, a time-of-flight (TOF) method [Gra80] is in use. An overview of all atomic masses measured with ISOLTRAP is given in Figure 3.1.

3.1.2 Highly charged ions for mass spectrometry

The advantage of using highly charged ions becomes obvious from Eq. (1): the cyclotron frequency scales linearly with the charge q of the ion. The resolving power achieved is approximately equal to the product of the cyclotron frequency and the excitation duration T_{ex} and the precision scales with the resolving power. In particular, the relative statistical mass uncertainty is given by

$$\delta m/m \approx m / (T_{\text{ex}} q B N^{1/2}) \quad (2)$$

where N is the number of detected ions. In order to obtain a high accuracy, i.e., a low mass uncertainty, high cyclotron frequencies due to strong magnetic fields or high charge states, and long interaction times are desirable.

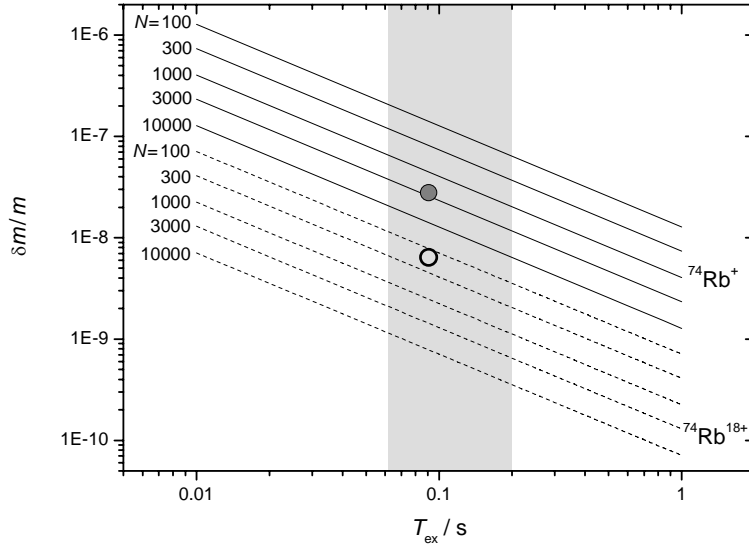


Figure 3.2: Mass uncertainty (see Eq. 1) for ^{74}Rb with a half-life of only $T_{1/2} = 65$ ms as a function of the excitation time in the Penning trap ($B = 5.9$ T) for two sets of charge states and different numbers of detected ions. The upper set of curves belongs to singly charged ions, the lower set of curves to ions in the charge state 18^+ which can be produced with the REX-EBIS within 20 ms. The grey-shaded area corresponds to an excitation time of about one to three times the half-life ($T_{\text{ex}} = 60\text{--}200$ ms). The grey dot gives the present accuracy limit obtained within ~ 7 radioactive beam shifts with ISOLTRAP in 2003 [Kel04]. The open circle indicates the accuracy limit of ISOLTRAP ($\delta m/m = 8 \times 10^{-9}$) [Kel03], which can be reached exploiting highly charged ions within one to two shifts for $^{74}\text{Rb}^+$.

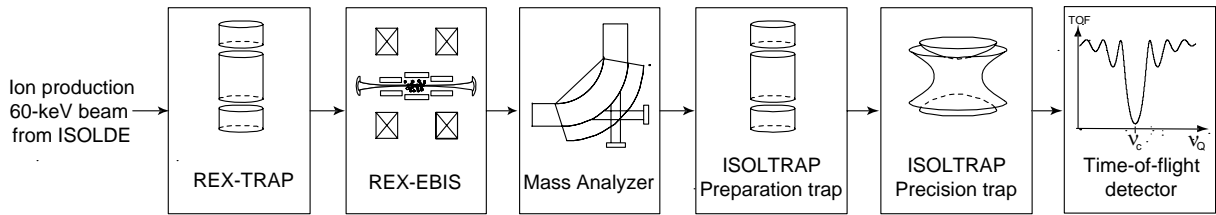


Figure 3.3: Schematic layout of the electron beam ion source (REX-EBIS) and the Penning trap system (ISOLTRAP)

For radioactive ions far from stability the interaction time is limited by the half-life, while the number of detected ions depends on the production yield and the available beam time. Since highly charged ions have higher cyclotron frequencies the resolving power and the accuracy are increased; or vice versa, a high-precision mass measurement can be performed in a much shorter time compared to the case of singly charged ions. This gives access to very short-lived nuclides, e.g., to the radionuclide ^{12}Be with $T_{1/2} = 21.5$ ms. Figure 3.2 shows the advantage of using highly charged ions with respect to accuracy in the case of ^{74}Rb with charge state 18^+ in a 5.9 T magnetic field.

3.1.3 Proposed technical realization

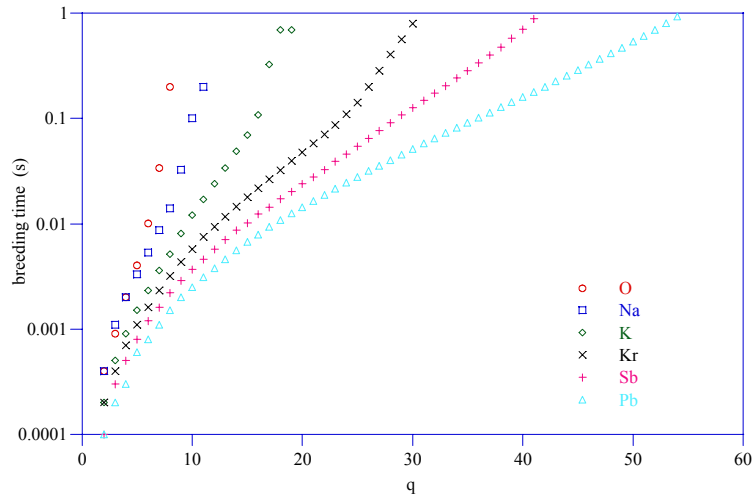
HIE-ISOLDE will offer several possibilities for the production and delivery of highly charged radioactive ions. One option is to combine the existing REX-ISOLDE electron beam ion source (REX-EBIS) and the Penning trap mass spectrometer ISOLTRAP at ISOLDE to exploit the advantages of highly charged ions for high-precision mass measurements. A schematic drawing of the proposed combination is shown in Figure 3.3.

Table 3.1: Peak charge-state after 20 ms breeding time

Element	Charge-state
${}^8\text{O}$	7^+
${}^{11}\text{Na}$	9^+
${}^{12}\text{Mg}$	9^+
${}^{18}\text{Ar}$	11^+
${}^{19}\text{K}$	11^+
${}^{20}\text{Ca}$	12^+
${}^{36}\text{Kr}$	16^+
${}^{37}\text{Rb}$	18^+
${}^{51}\text{Sb}$	19^+
${}^{54}\text{Xe}$	21^+

At present the only electron-beam ion source trap in operation for charge breeding of short-lived radionuclides is REX-ISOLDE at CERN for post-acceleration experiments¹. With a 5 keV electron beam and a current of 0.5 A a current density of $>200 \text{ A/cm}^2$ throughout a 0.8 m long trap region can be obtained in the charge breeder. With these parameters the REX-EBIS trap at ISOLDE/CERN can hold $\sim 6 \times 10^9$ charges for an electron-beam charge-compensation of 10% [Wen01]. The most dominant charge states for some typical ions, charge bred for 20 ms in an EBIT with the parameters given above, are listed in Table 3.1. Figure 3.4 shows the breeding time as a function of charge state for some selected elements.

An alternative approach for the delivery of highly charged ions to the ISOLTRAP mass spectrometer is the installation of a second EBIS (the same type as REX-EBIS) at ISOLDE, which can be combined with the RFQ cooler of ISOLTRAP. This would allow an independent operation from REX-ISOLDE as well as a simpler modification of the ISOLDE beamline.

**Figure 3.4:** Breeding times as a function of the charge state for a current density of 200 A/cm^2 (courtesy of F. Wenander [Wen01])

¹ Another facility is planned in the framework of the TITAN project at TRIUMF, which is also aiming for high-precision mass measurements on ISOL type produced radionuclides. First TITAN tests are planned for 2007.

A short storage time of only a few tens to a hundred milliseconds and a vacuum of $p \leq 10^{-9}$ mbar should be sufficient for requirements with respect to ISOLTRAP. This is better than the present vacuum conditions at the precision trap, for which recent mass measurements on stable, doubly charged xenon nuclides showed charge exchange losses for longer storage times [Her06]. The vacuum can be improved by adding getter pumps to the current ISOLTRAP system. Of course helium buffer gas cooling — at present in use at ISOLTRAP in the radiofrequency cooler and buncher and in the preparation Penning trap — cannot be used

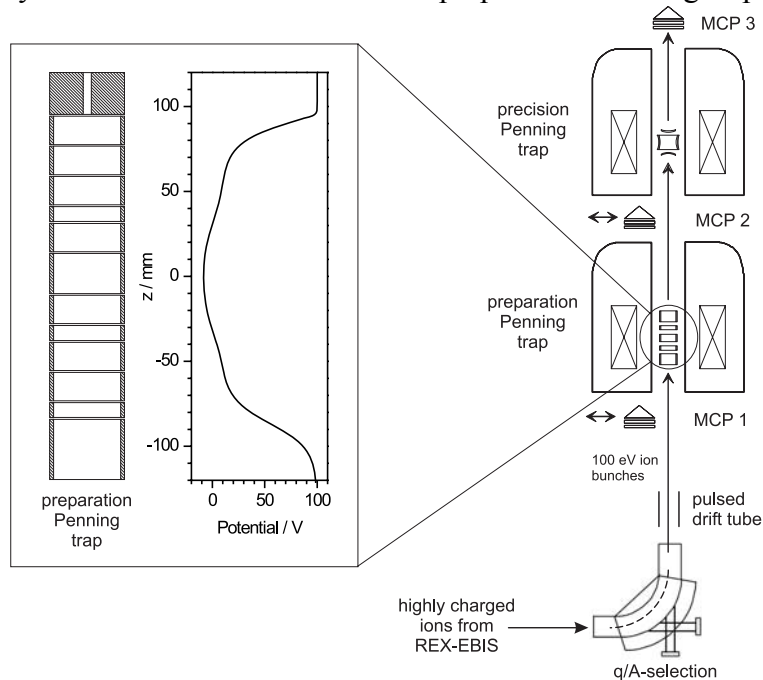


Figure 3.5: Modified experimental setup with a q/A -selection that replaces an electrostatic bender. The inset shows the current electrode configuration of the preparation Penning trap and the applied potential along the axis.

in the case of highly charged ions because of charge-exchange losses. Therefore, in a first step one can shoot through the buncher and use evaporative cooling in the preparation trap, i.e., throwing away the hottest ions and reducing the overall efficiency by about two orders of magnitude.

However, for high-precision mass measurements the number of ions stored in the precision Penning trap at a given time is reduced to one in order to avoid frequency shifts due to ion-ion interactions. Note that the current cylindrical Penning trap (see inset of Figure 3.5) allows the application of evaporative cooling without any change of the electrodes. Only for the lowering of the potential well depth is a slight modification of power supplies necessary.

In a second step the currently achieved efficiency can be re-established by adding electron and resistive cooling (see Figure 3.6) as planned in the HITRAP project at GSI for stable or long-lived isotopes [HIT03]. Also, sympathetic cooling with laser-cooled ions might be an efficient way to prepare the ions.

While the preparation trap is currently also used for purification of the ion ensemble as delivered by ISOLDE, an additional q/A selection step for the ion beam on its way from REX-EBIS to ISOLTRAP is needed and already included in the proposed scheme. The charge breeding at REX-EBIS provides further parameters for the reduction of contaminants. In addition, the selection of appropriate charge states of the ions of interest and the ions for the magnetic-field calibration will lead to closer mass doublets and, thus, to a further increase of

accuracy. As a possible experimental scheme a q/A selection in front of the preparation Penning trap is shown in Figure 3.5.

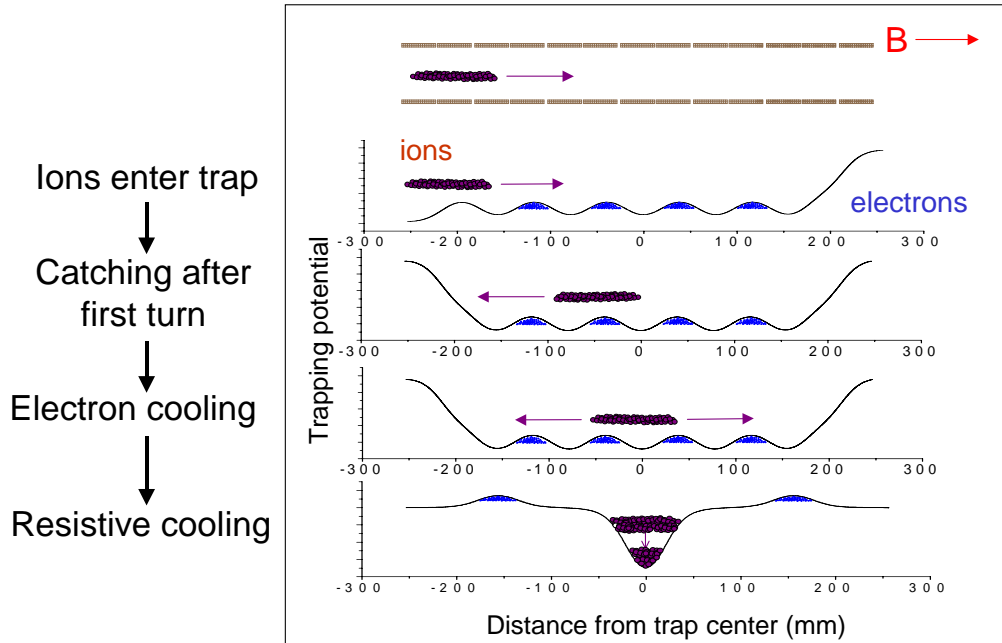


Figure 3.6: Experimental scheme of electron and resistive cooling in a cylindrical Penning trap (courtesy of Wolfgang Quint, GSI)

3.1.4 Conclusion

In conclusion, the unique combination of an electron-beam ion source to produce highly charged ions and a Penning trap mass spectrometer for high-precision mass measurements installed at ISOLDE/CERN will be the most powerful technique for mass spectrometry on short-lived exotic nuclei. Increased accuracies and a further reduction in the lower limit of the half-lives as compared to the present values are expected.

3.2 Laser spectroscopy

Laser spectroscopy possesses the speed and sensitivity to perform measurements of nuclear moments, spins, and nuclear mean-square charge radii on radioactive isotopes [Ott89, Bil95, Klu03a]. Experimental groups working at ISOLDE have made a considerable contribution to this field over the last 25 years. The current status of the measurements is shown in Figure 3.7. The ability to push these measurements of fundamental nuclear properties further, both towards the proton dripline and into the neutron-rich regions will be greatly enhanced by the higher beam intensities, beam-tailoring techniques with ion coolers, and the increased isobaric purity of the beams that HIE-ISOLDE will provide. The motivation for studying the structure of these exotic systems is well documented and forms the science case [EurRep] of the new and proposed radioactive ion-beam facilities such as EURISOL. Although nuclear reactions using the planned RIB facilities feature prominently in the proposed research, there are equally powerful and complementary techniques, such as laser spectroscopy, which require only low-energy ion beams.

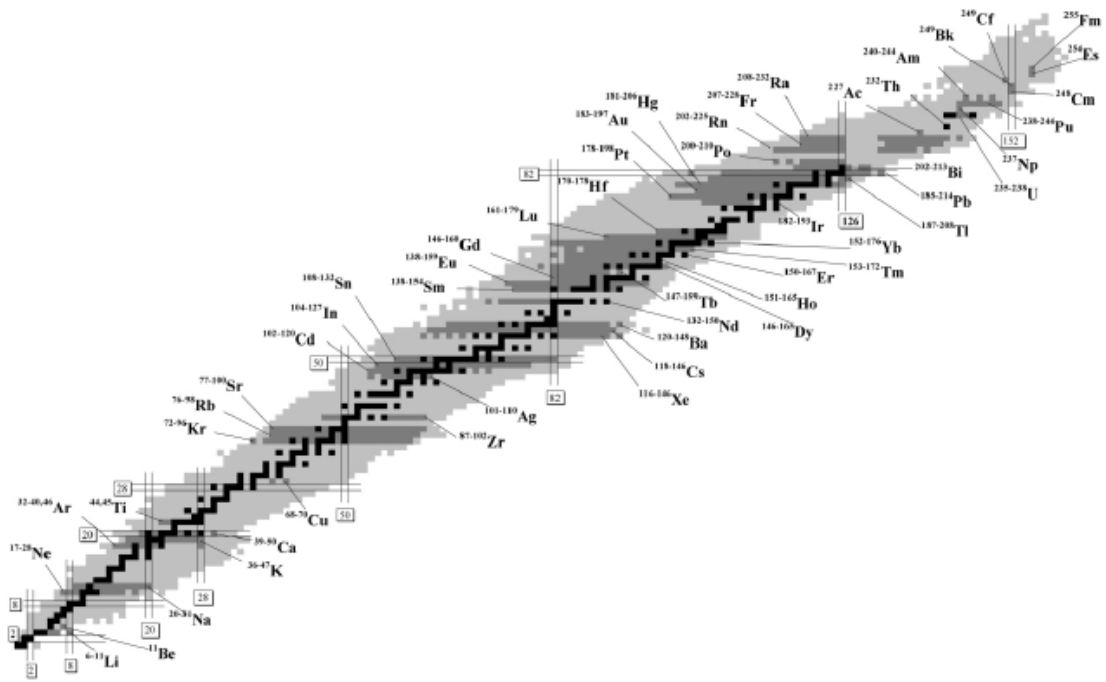


Figure 3.7: Status of on-line optical measurements taken from ref. [Klu03a]. Black squares indicate stable nuclei. Light-grey squares indicate nuclei known to exist as bound systems.

3.2.1 Methodology

In general, the laser frequency is scanned across an optical resonance of the atom. The fluorescence photons (or other signature of the excitation, such as state-selective ionization) can then be counted producing an optical spectrum of sufficient resolution as to resolve the constituent hyperfine structure.

The example in Figure 3.8 shows the hyperfine structure of the 4-second 1147 keV ^{178}Hf $I = 8$ isomer [Bis07]. The ground state, having a spin value of zero, appears as a single peak. The interaction of the atomic electrons with the nuclear magnetic and electric quadrupole moments lifts the degeneracy of the upper and lower atomic levels involved in this transition. From these splittings the moments may be deduced.

The centroid of the isomer structure is not coincident with that of the ground state. This change in frequency between isotopes of an element, or isomeric states, is known as the isotope (or, in this case, isomer) shift. The change in the nuclear mean-square charge radius between isotopes is a fundamental quantity which may be extracted from isotope shift measurements with little model dependency.

The mean-square charge radius is a measure of not only the changing nuclear volume but is also sensitive to the total deformation (static and dynamic) and nuclear surface diffuseness. The static quadrupole parameter from the quadrupole moments can be used to correct spherical-droplet-model charge radii estimates and the correspondence with those from isotope shift data can be a qualitative indicator of the softness of the deformation or the presence of higher order multipoles.

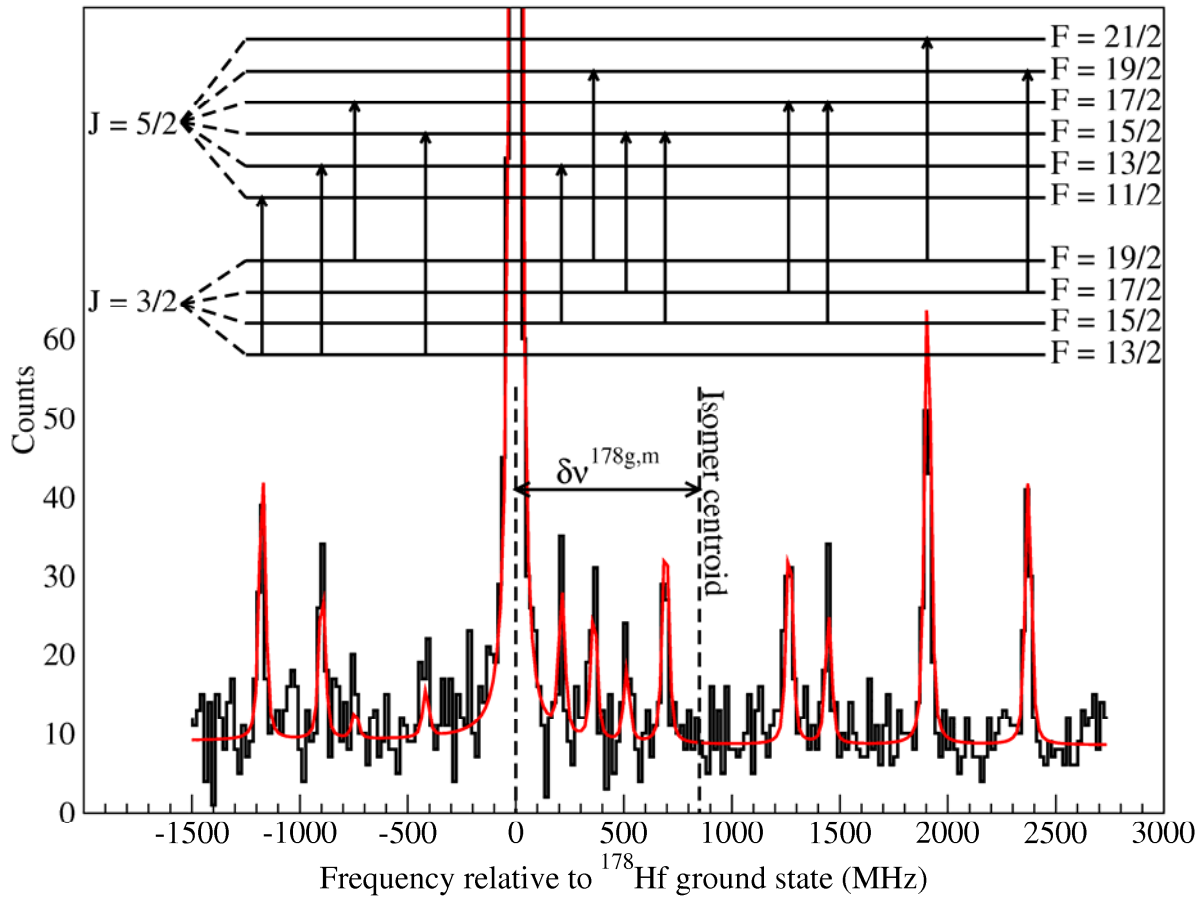


Figure 3.8: Optical spectrum of the hafnium $A = 178$ ground state and 1147 keV ($\tau = 4$ s) isomer measured on the 301.3 nm line in the Hf^+ ion using collinear laser spectroscopy

For the example given in Figure 3.8, analysis of the isotope shift has shown the mean-square charge radius for the (multi-quasiparticle) isomeric state to be smaller than for the ground state despite an increase in static quadrupole deformation as determined from the hyperfine splitting.

3.2.2 Laser work at ISOLDE

Collinear-beam laser fluorescence spectroscopy has been used at ISOLDE by the COLLAPS group [Bor05, Fla05, Gei99, Gei05, Kow05, Ney05]. The laser beam interacts collinearly with a 60 keV ion beam. An additional tuning potential is applied prior to the measurement region which acts to bring the ions into resonance with the (Doppler-shifted) laser frequency. A photo-multiplier tube counts the fluorescence photons as the tuning potential is ramped, producing the optical spectrum. Collinear arrangements maximize the volume of overlap of laser and ion beams while the acceleration to typically 60 keV compresses the velocity spread in that direction, thereby reducing the Doppler broadening to a level comparable with the natural linewidth of the resonance.

The sensitivity of the technique depends on the efficiency of photon detection and the background rate of the scattered photons from the laser beam. Related methods have also been employed by the group [Neu86, Shu91, Sil88] to improve the sensitivity. For example, resonance ionization spectroscopy uses a powerful second laser to ionize atoms which have been resonantly excited by the first laser. The ions are then detected instead of photons.

The COMPLIS Collaboration at ISOLDE has made spectroscopy measurements on some refractory elements using a laser resonance ionization method [LeB00, LeB02, LeB04, LeB05, Sau00]. Refractory elements are not produced with a sufficient flux at ISOLDE for successful collinear-beam experiments but these have been studied by implanting a radioactive beam of parent nuclei onto a rotating graphite substrate. The atoms of the isotopes of daughter products are then laser-desorbed and resonantly ionized by two- or three-step processes and the ions are counted. As the implanted sample is stationary, the first excitation step uses a high resolution laser which performs a frequency scan over the region of interest. The second laser then has sufficient energy to excite (only) the resonantly excited states to the continuum.

The atomic fine structure lines are extensively tabulated for a large range of elements and these are now widely and increasingly used at ISOLDE for isotope production using the Resonant Ionization Laser Ion Source (RILIS) [Fed04, Fed05, Fed06, Kos00, Kos04] to improve both the yield and the isobaric purity of the extracted beam. By using a narrower bandwidth (~ 1.2 GHz) laser for the first step of excitation, in-source laser spectroscopy may also be performed [Fed03, Kos00a, Sel06, Wei02] before the resonantly produced ions are accelerated from the source. Particle detectors can then monitor the flux as a function of laser frequency to locate the hyperfine resonances or further analysis may be performed simultaneously such as alpha- or beta-decay studies. Although the laser resonance has the full Doppler broadening characteristic of the ion source temperature, the technique is suitable for elements with a large spacing of hyperfine components (found typically in heavier elements) and offers a high spectroscopic sensitivity, requiring a sample flux of only tens of atoms per second.

3.2.3 New opportunities at HIE ISOLDE with an ion cooler

An ion-beam cooler–buncher, ISCOOL, is in the process of being constructed and tested prior to installation in the ISOLDE hall on the HRS line [Jok03, Pod04, Pod04a, Pod05]. The device is placed on a high voltage platform at a potential slightly lower than the incoming beam energy and consists of a gas-filled, longitudinally segmented, RF quadrupole. The ions decelerate on entry to the device and are thermalized in the buffer gas. A weak axial field is created by the segments causing the ions to drift towards the trapping region at the end. Here the ions are accumulated to be released in bunches if desired. On re-acceleration from the cooler the beam is decoupled from the properties of the primary beam and possesses a smaller emittance and a longitudinal energy spread of less than 1 eV.

A similar device has been operating at the JYFL IGISOL [Ayo01], Jyväskylä, where the data of Figure 3.8 were taken. The measurement was possible only because of the improved spatial overlap of the laser and ion beams obtainable with the lower emittance and the reduced Doppler broadening of the peaks from the longitudinal energy spread [Cam02, Nie02]. The ability to release ions in bunches dramatically reduces the background by accepting only the photons counted during the period that an ion bunch is traversing the interaction region (see Figure 3.9). Measurements have been made with fluxes of a few hundred ions per second.

Following each proton pulse delivered to the HRS during the supercycle, the ions diffuse out over a period of around 0.5 s depending on the element and ion source used. The cooler can accumulate the ions during that time and release them in a few-microsecond bunch for the collinear beams laser measurement. The continuous background due to scattered laser light is thus suppressed by 3 or 4 orders of magnitude (see Figure 3.9). In applications where the ion cooler provides beams for collinear resonance ionization measurements, the bunch arrival

time can be synchronized with the pulsed laser to eliminate duty losses, even for low repetition rate (10 Hz) systems.

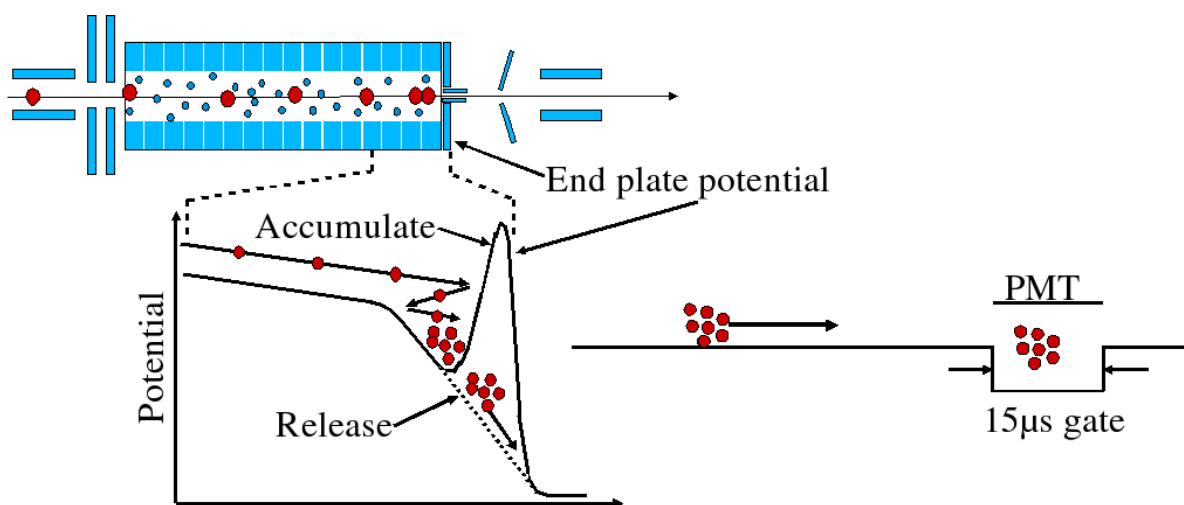


Figure 3.9: Schematic showing the ions drifting towards the end of the cooler where a trapping potential accumulates them before bunched release. Only photons detected during a gate defining the ion-bunch and laser interaction time are counted.

The choice of optical transition for the spectroscopy measurement is normally limited because the atoms (or ions) are formed either in the ground state or low-lying metastable states. However, the radial localization of the trapped or slowly emerging, cooled ions at the end of the cooler provides an opportunity to pump transitions to redistribute the state population. This may be done using broadband lasers which can readily access a wide range of wavelengths.

Manipulation of state populations in this way opens up the choice of transition for study by collinear techniques. States may be chosen on the basis of preferred spins, hyperfine structure, or transition strength from the level. An example of the necessity for such an approach is provided by recent studies on yttrium. Isotopes and some isomers from $A = 86$ to 102 were measured by laser spectroscopy [Che07]. In order to extract nuclear data from the observed spectra at least one of four nuclear parameters must already be known — either the nuclear spin, magnetic moment, quadrupole moment, or charge radius relative to a known system. This situation arises as the $J = 0$ ground-state term limits the possible upper ionic terms to $J' = 1$ states and only three hyperfine components can be observed. There was thus insufficient information for a unique analysis of three structurally important systems, namely the ^{98m}Y isomer, ^{100}Y and ^{102}Y , where an independent evaluation is required.

Figure 3.10 shows two resonance fluorescence spectra observed in a collinear fast beam study of the stable ^{89}Y ion (using a continuous 1 pA flux of ions). For both spectra the optical transition was excited from the same metastable state and the effect of optical pumping in the ion cooler can be observed. The 321.7nm ($J = 2$ to $J' = 1$) line provides all four nuclear parameters, but is less efficient. However, during the acquisition of the spectrum labelled “363 on” ~ 200 mW of 363.3 nm light from a pulsed titanium-sapphire laser illuminated the thermalization axis of the cooler and is seen to double the efficiency [Cam06].

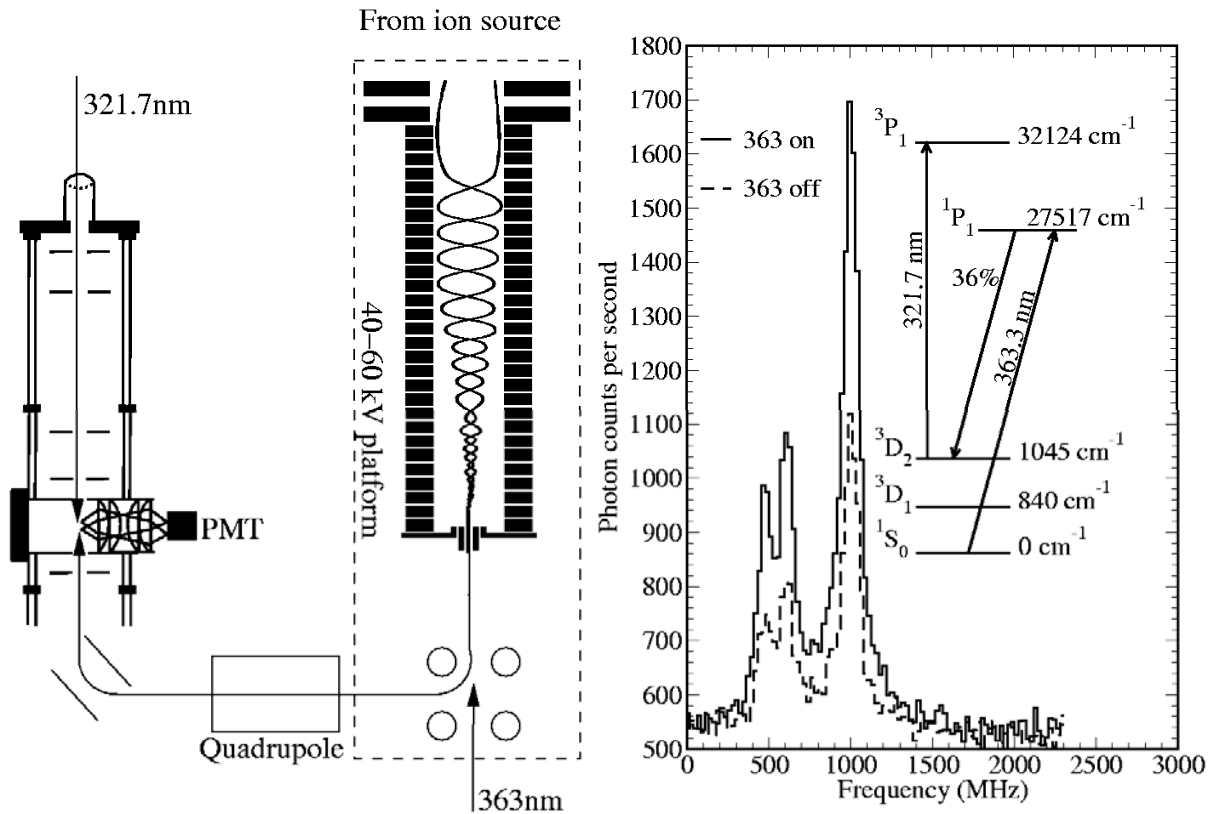


Figure 3.10: An illustration of laser light illuminating the ions on exit from the cooler before high-resolution collinear interrogation (left). Also shown is an yttrium $A = 89$ ground-state resonance with and without pumping (right).

Optical pumping in an ion cooler has thus already proved useful for laser spectroscopy studies. Future applications could involve pumping schemes using circularly polarized light to produce ion beams with a nuclear polarization, such as is required for β -NMR measurements.

In summary, the sensitivity of laser spectroscopy techniques can be improved with an ion cooler, not just through the reduced emittance and energy spread of the beam, but also through the ability to tailor the time structure, atomic state population, and nuclear polarization of the ion beam. Coupled with increased fluxes and isobaric purity from the ion source and the continual improvement of laser technology and available wavelengths there is tremendous scope for extending studies to exotic nuclei further from the valley of stability than has hitherto been possible.

3.3 Nuclear moments

Magnetic moments of nuclei provide an important input for the understanding of nuclear structure since they can provide precise and unique information regarding the single-particle nature of the particular nuclear level under study. In addition, the nuclear quadrupole moments give direct information on the nuclear deformation and are an indispensable part of nuclear structure knowledge. In the last few years, there has been much focus on probing nuclear structure at extreme isospin, using the various new developments in rare-isotope-beam facilities and in ancillary detection systems. A large number of these studies have been performed at the currently running ISOLDE facility and they can be developed largely with the construction of HIE-ISOLDE which should provide superior beams both from the point of view of intensities as well as the variety of beam energies. Here we would like to discuss how nuclear moment studies can benefit from the improved characteristics of the REX post-accelerator.

Since the techniques for nuclear moment studies are highly specific and strongly dependent on the life time and the decay type of the nuclear states, we would like to consider two main groups; namely, ground-state studies and nuclear moments of excited short-lived and isomeric states.

3.3.1 Ground states

In order to perform a nuclear moment study on ground states of radioactive nuclei one needs a spin-polarized nuclear ensemble. There is a variety of techniques to obtain a polarized nuclear ensemble, and mention can be made of the reaction polarization, optical pumping and Low-Temperature Nuclear Orientation (LTNO) [Bor02, Gin00, Rik00 and references therein]. Some of these, such as the LTNO (NICOLE) and the optical pumping (COLLAPS), are already present at ISOLDE and giving fruitful results. There are two ideas for further development at HIE-ISOLDE: nuclear polarization in the RFQ cooler/buncher, discussed in Section 3.2.3, and the tilted-foil nuclear polarization.

A tilted-foil set-up at the low-energy section of REX-ISOLDE

Measurements of ground-state magnetic moments in short-lived, proton-rich nuclei can shed much light on the evolution of shell structure when approaching the proton dripline. The β -NMR method has been widely used in such measurements of unstable nuclei (its use in condensed matter studies is discussed in Section 2.6.2). The asymmetric distribution of decay β -particles, resulting from the initially obtained polarized ensemble, is monitored in the presence of an external static magnetic field and a perturbing rf field.

The particular method chosen for polarizing a given nucleus depends mainly upon properties such as lifetimes and atomic structure. For short-lived nuclei in the ms range, or for elements not readily amenable to laser techniques, the tilted-foil method has a broad potential when combined with the β -NMR technique. In tilted foil (TF) geometry, atomic polarization is initially induced in ionic electrons by a surface interaction upon the exit of an ion from a thin foil, tilted at an oblique angle with respect to the ionic beam direction. The atomic polarization (in the direction $\mathbf{n} \times \mathbf{v}$ — where \mathbf{n} is the unit vector perpendicular to the outgoing surface of the foil and \mathbf{v} is the ion velocity vector) is transferred to the nucleus via hyperfine interaction. The nuclear polarization thus induced can be enhanced, especially for high-spin states, by the use of several foils spaced sufficiently so as to allow a significant nuclear precession around the total angular momentum in the flight time between successive foils.

Experimental considerations

In previous experiments at ISOLDE, the magnetic moments of the ground states of $T = 1/2$ and $T = 3/2$ nuclei in the sd shell, ^{23}Mg and ^{17}Ne , respectively [Bab04, Lin00], have been measured by using the High-Voltage Platform (HVP) at -200 kV. The HVP has been constructed at ISOLDE to boost the initial energy of the 60 keV beams. This boost in energy is essential in order to provide the nuclei under study with sufficient energy to traverse one or two carbon foils tilted at 75° to the beam direction. In the first experiment, owing to the high yield of ^{23}Mg , it was possible to use the 10 times scarcer 2^+ charge state in order to obtain a total of 520 keV. However, for nuclei far-from-stability, the beam intensity usually does not allow the use of ions with charge states other than 1^+ . For ^{17}Ne , because of the lower Z , singly charged ions were used. However, for $\sim Z > 12$, much higher energies are needed and we therefore propose to use REX-ISOLDE for this purpose.

The necessary use of the HVP poses several experimental difficulties which the proposed use of REX-ISOLDE for such an experiment will alleviate.

- Even at 520 keV energy, the multiple scattering in the tilted foils resulted in a loss of more than 50% in the beam reaching the stopper and the rf region, diminishing considerably the accuracy and systematic reliability of the measurement. It is especially important when trying to measure magnetic moments of nuclei in the f shell, with masses in the $A = 50\text{--}70$ range, for which the laser ion source at ISOLDE is capable of producing good beams. These nuclei will be the focus of this phase of the research programme and provide a complementary method to similar studies using beam polarization at intermediate energies now being planned at the NSCL Lab at Michigan State University.
- Tilted-foil polarization is an atomic effect, depending on the hyperfine interaction of the atomic configurations in the particular charge states emerging from the tilted surface at a given velocity. When using the HVP, this velocity is necessarily fixed at a low value. REX-ISOLDE will provide the opportunity to probe the induced TF polarization at a wide velocity range and thus find the optimum conditions for any particular nucleus, or region of nuclei, under study, greatly enhancing the sensitivity of the method.
- Carrying out experiments on the HVP is a complicated and time-consuming procedure as any access to the experimental apparatus is restricted and involves a complicated and elaborate sequence of events. This will automatically be remedied in the proposed set-up.

With the construction of the new Extension Hall at ISOLDE, several experimental set-ups such as the MINIBALL array, that need higher REX energies, have moved to the new hall. This will facilitate the transfer of the superconducting magnet and the tilted-foil chamber from their present location on the HVP. The energies needed for the tilted-foil polarization may vary widely, from values obtained by using only the RFQ device up to 1–2 MeV/A, and hence can be best obtained at this location.

Requirements

- *Physical space and infrastructure:* The minimum requirements are: 1) A short beam line after the switching magnet behind REX. 2) A stand to support the superconducting cryostat and the tilted foil chamber. 3) A return line for He gas.
- *Beams and yields:* From the brief discussion above, the nuclei under consideration are the $Z = N+1$ isotopes in the f-shell (e.g., ^{57}Cu , ^{53}Fe , etc.) and $T = 3/2$ nuclei in the s-d shell (e.g., ^{21}Mg , ^{33}Ar etc.). The largest unknown when trying to assess the needed yield for a β -NMR measurement is the nuclear polarization in the tilted foil method. This essential quantitative parameter depends on the velocity and charge state of a given RNB beam and its behaviour will become better known as experiments progress. For a present rough estimate we can generally follow the results of the previous ^{23}Mg and ^{17}Ne experiments (see Figure 3.11) and assume $A_\beta \sim 1\text{--}2\%$. For these figures, yields of 100–1000 ions/s into the apparatus should be sufficient for a successful determination of a β -NMR resonance. These yields are a realistic goal for the aforementioned beams at HIE-ISOLDE.
- The determination of quadrupole moments of ground states is also possible using the TF polarization and β -NMR when implanting the polarized RNBs into a non-cubic crystal. Such determination will provide unique and complementary information on the deformation of the nuclear shape in far-from-stability regions. However, in general, a quadrupole moment determination is more difficult on account of the different frequencies in the β -NMR spectrum when compared to the magnetic case. As a consequence, the quadrupole measurement phase will only come when sufficient information is gained about the systematics of the TF polarization.

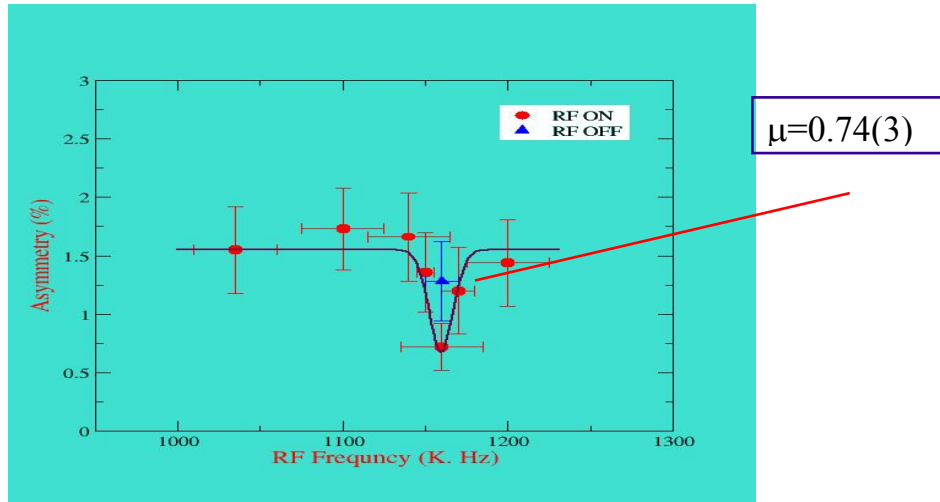


Figure 3.11: β -NMR resonance curve for ^{17}Ne [Bab04]. An asymmetry of $A_\beta \sim 1.5\%$ was obtained

3.3.2 Excited states

The magnetic moment of an excited state provides unique information about its wavefunction composition. Owing to the very different single-particle g -factors of protons and neutrons in different orbitals, it is in many cases possible to deduce the relative weight of the different single-particle configurations for a certain state of interest. For short-lived excited states for which the interaction time of its magnetic moment with external or static hyperfine fields is too small to induce a measurable effect, two complementary techniques are available for g -factor measurements.

The techniques of transient fields and recoil in vacuum

In the **transient field technique** the $1s$ electrons of the ions of interest are polarized during their passage through a ferromagnetic target layer via spin exchange interactions with the polarized electrons of the ferromagnetic host. The hyperfine interaction between the nuclear spin, aligned due to the reaction kinematics, and the oriented electron spin leads to a precession of the nuclear spin about a fixed axis (given by the direction of the external magnetic field) and thus to an observable *rotation of the angular distribution* of the gamma-rays emitted in the decay of the state. This technique has been applied for many years in stable beam experiments. A particularly successful version of this technique, namely its application to excited states populated in Coulomb excitation in inverse kinematics at beam energies of a few MeV/u, has been developed in recent years by the group at the University of Bonn [Spe01]. Although so far it has mainly been applied to stable ion beams, a first test of its application to radioactive beams was performed last year at REX-ISOLDE and the measurement of the first 2^+ g -factor in ^{138}Xe using the transient field technique will follow this year.

The second technique of choice for the measurement of magnetic moments of short-lived excited states is the **recoil-in-vacuum** (RIV) method. Here, the nuclei in the excited state of interest, populated, for example, by Coulomb excitation, leave the target and recoil into vacuum. In this case the electron spins are randomly oriented and the hyperfine interaction between them and the aligned nuclear spin leads to a precession of the nuclear spin about random axes. The net effect in this case is the observation of an *attenuation of the angular*

distribution of the subsequently emitted gamma-rays. This technique has recently been successfully applied for the first time in a radioactive beam experiment at Oak Ridge to measure the g-factor of the first excited 2^+ state in ^{132}Te [Sto05] (see Figure 3.12).

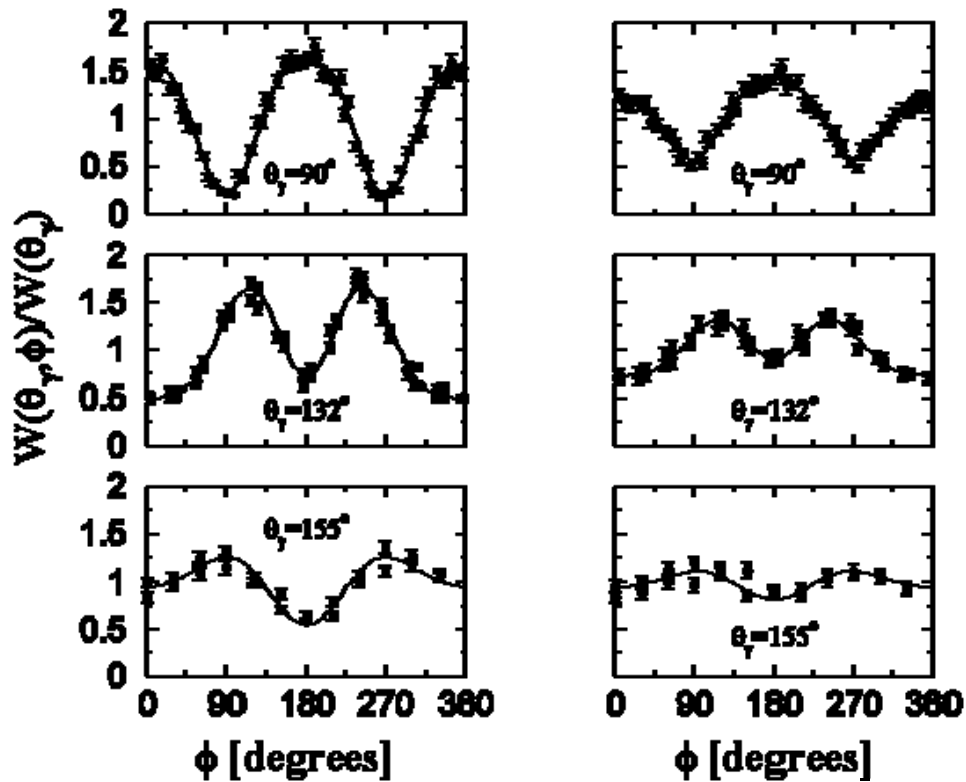


Figure 3.12: Unattenuated (left) vs. attenuated (right) angular correlations for the decay of the 2^+ in ^{130}Te . For more details see Ref. [Sto05].

Both techniques can be applied at the HIE-ISOLDE facility using either part of or the full MINIBALL array for gamma-ray detection. The TF technique has the advantage that it gives the sign of the g-factor which in many cases is very crucial information, and that it needs only one calibration point for the transient field strength which can easily be obtained from a parallel measurement of a stable isotope. Disadvantages are the need for good statistics, since the precession angles to be measured are very small and only detectors in or close to the plane perpendicular to the field direction can be used. The advantages of the RIV technique, on the other hand, are that relatively poor statistics may still yield useful g-factor information (all detectors in a 4π array can be used to measure the attenuation of the angular distribution) and that it is completely compatible with other spectroscopic studies as no special target is required. Weak points of this method are a limited lifetime range, the need for a couple of calibration points (and certain model dependence in the calibration procedure), and that no sign information can be deduced.

Nuclear transfer reactions for moment measurements of short-lived isomeric states

Up to now nuclear moments of short-lived isomeric states of neutron-rich nuclei far from stability have been measured only in projectile-fragmentation reactions [Geo02, Mat04]. This method has proved its strong potential. However, it has a serious shortcoming inherited from the production and selection mechanism of the nuclear states of interest. Since the production

target and the implantation point should be decoupled in space and one needs to use a fragment separator in order to select specific isomeric states, it has a limitation of the shortest measurable lifetimes of the isomeric states. Even for relativistic energies the time of flight of the ions through the separator is of the order of 200 ns, which together with the bremsstrahlung at higher energy (~few hundreds of ns) puts the limit of the shortest measurable isomeric states between ~200 ns, in the most favourable cases, and ~1000 ns in the least favourable ones. This method also needs much higher energies, of the order of a few tens of MeV/u, not accessible even at HIE-ISOLDE. Therefore, it is worth while working on the development of a new approach for nuclear moment studies of short-lived isomeric states with post-accelerated beams.

The nuclear transfer reaction has been used to a certain extent for nuclear moment studies throughout the years. However, owing to the relatively lesser degree of alignment obtained in these types of reactions, they were not favoured with respect to the fusion-evaporation reactions, for example. The use of fusion-evaporation reactions with radioactive beams is expected to cause more experimental difficulties, such as lower cross-sections compared to the transfer reactions and higher background at the target position caused by the stopped radioactive beams and, therefore, one is redeveloping the application of transfer reactions in inverse kinematics with radioactive beams.

The recent experience in the application of transfer reaction for the study of short-lived isomeric states has shown that the amount of nuclear alignment obtained can vary between 10–15% in a single-nucleon transfer at energies around the Coulomb barrier up to more than 40% in multinucleon transfer (pickup) reactions at energies well above the Coulomb barrier (see Figure 3.13). These values are obtained without any particle- γ correlations and from this point should be considered only as the lower limit of the alignment obtainable in these reactions. The application of particle- γ correlations in inverse kinematics reactions with radioactive beam can only increase these values and make this type of measurement easier to perform.

One of the main advantages of the use of transfer reactions for nuclear moment studies with radioactive beams is that there is practically no limit to the lifetime of the accessible isomers. This opens up a much larger variety of nuclear states far from stability for these measurements. Especially interesting regions are the nuclei close to shell closures, where one expects to uncover a number with large variations in their lifetimes. For the regions around the neutron-rich $N = 50$, $Z = 50$, $N = 82$, etc., where the development of the shell structure is not very well understood, the nuclear moments with their sensitivity to single-particle components and purity of the nuclear wave function (magnetic moments) as well as to the nuclear deformation (quadrupole moments) can provide indispensable information.

HIE-ISOLDE advantages and requirements

Nuclear magnetic moment studies will certainly benefit from the increased intensities available at HIE-ISOLDE. Of special interest for the nuclear moment studies in transfer reactions is the increased energy of the post-accelerated beams. With the present possibility of 3 MeV/u one is just at the limit of performing these reactions for light nuclei. With the increase of REX energies to 5 MeV/u and, in the next step, up to 10 MeV/u one should have the possibility of applying the full range and variety of transfer reactions from the single-nucleon ones at the Coulomb barrier up to the multi-nucleon transfers at higher energies.

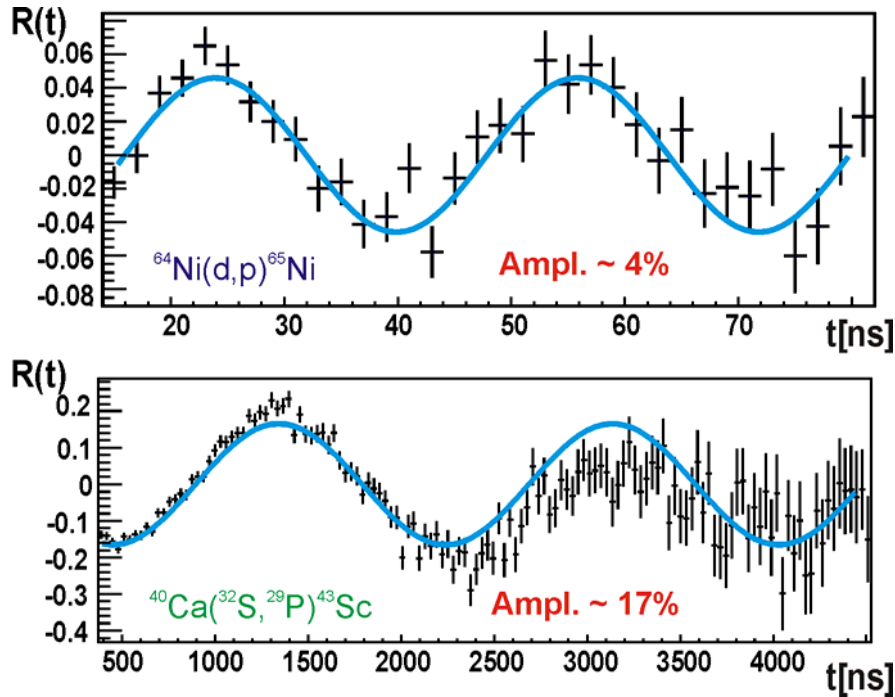


Figure 3.13: $R(t)$ functions from TDPAD measurements from $^{64}\text{Ni}(d,p)^{65}\text{Ni}$ reaction with 6 MeV deuteron beam [Geo05] (upper part) and $^{40}\text{Ca}(^{32}\text{S}, ^{29}\text{P})^{43}\text{Sc}$ with 120 MeV ^{32}S beam (lower part)

An important point in the application of these techniques is the time structure of the post-accelerated beam. At present the natural microstructure of the REX Linac of micro-pulses at 10 ns time difference superimposed on the macrostructure of EBIS and Linac of macro-pulses with microsecond length at 50 to 100 Hz repetition rate makes any time-differential measurements practically impossible in bare form (i.e. using standard stable-beam techniques of beam pulsing of $\sim 1\text{--}2$ ns at a period of few hundreds of ns.) Therefore, one is forced to use the particle- γ correlations in order to obtain the time-reference for the measurements. However, this technique is still not sufficiently developed and proven to work and it also cannot be used at very high beam intensities such as those expected to be available at HIE-ISOLDE. Therefore, a solution for the pulsing of the REX Linac beam on the time scale of 100 ns to 1 μs should be found. The superconducting solution for the REX Linac should allow, at a certain stage, the suppression of the currently unavoidable duty cycle of the room-temperature one and subsequently lead to more even distribution of the beam intensity in time. Not only the nuclear moment measurements but any other experiment will clearly benefit from such improved conditions, which will certainly decrease the detector loads and diminish the acquisition dead-time.

3.4 Decay studies

3.4.1 Beta decay studies

The body of knowledge on the structure of exotic nuclei is collected from many different types of experiments carried out with stable and radioactive beams. Beta-decay is an established probe of nuclear structure, of special interest at the driplines, which gives access to the most basic properties of a nucleus, as the decay half-life and main decay modes. This information can be obtained with relatively low beam intensities, which makes the characterization of these properties of exotic nuclei readily accessible. Furthermore, the population of excited states of the daughter nucleus, and the observation of the radiation associated with their de-excitation yield invaluable spectroscopic information on the energies

and characteristics of the low-lying excited states. It also gives access to the investigation of other important characteristics such as the multipolarity and strength of the transitions, providing direct insight into the nuclear structure of the daughter nuclei.

A large variety of different beams with large intensity is needed to perform beta-decay studies at HIE-ISOLDE, both for neutron-rich and neutron-deficient nuclei. The potential of several types of experiments will be increased by extending the wide range of available elements at ISOLDE and achieving higher intensities. The target development programme needs to be continued to include, for instance, negative ion sources, ECR ion sources, and new target materials.

The upgrade of the beam selectivity through various techniques for beam preparation is required to provide isobarically pure beams for improved sensitivity and low background for the experiments. A small beam size can prove very important for certain classes of experiments.

The experiments may benefit from the possibility of cooled and bunched beams by means of an RFQ cooler and buncher for an increase of beam purity and instantaneous intensities. Polarized beams, obtained for example from the RFQ cooler by optical pumping, would allow for new information to be obtained in beta-decay spectroscopy and significantly broaden the physics observables related to weak interaction studies.

Specifically for the Standard Model tests involving precision mass measurements as well as beta-neutrino correlation and beta-asymmetry measurements, yields of at least 10^3 (masses) or 10^7 (correlations) particles per second are required for superallowed pure Fermi beta decaying isotopes, $T = 1/2$ mirror nuclei and selected isotopes with low-energy (< 1 MeV) pure Gamow–Teller transitions. The HIE-ISOLDE facility will significantly extend the number of available isotopes of interest for these measurements, and in addition provide much increased yields for isotopes that are already available now. In all cases high-purity beams are required.

A new application for Penning traps at radioactive-beam facilities has recently emerged. The technique, known as trap-assisted spectroscopy, has been developed over the last three years by the JYFLTRAP group in Jyväskylä [Jok05, Jok06, Rin07]. It uses the traps to isobarically, and even isomerically, purify the beam of interest and to perform decay studies on it. This novel approach paves the way for investigations hampered up to now by high isobaric and isomeric contamination.

Following this development, in 2006 and 2007 the REX team at ISOLDE provided a purified molecular beam of ^{38}Ca for precise half-life measurements [Bey07, Bla05a]. Currently, a tape-station decay-spectroscopy system similar to that in Jyväskylä is being designed and will soon be placed behind the ISOLTRAP set-up. An experiment investigating beta and gamma decay of neutron-rich Hg and Tl isotopes [Kow07] using this set-up has recently been accepted by the ISOLDE scientific committee and the first measurements should take place in 2008. Once operational, the set-up will serve various purposes ranging from isobaric purification for decay studies, to assistance to mass measurements when one cannot resolve the ground and isomeric state.

Correlation techniques for decay studies

In decay spectroscopy, the signature of a particular channel is rarely given by a single signal: prompt and delayed *correlation* between different kinds of radiation is necessary to identify

the decay route and build the schemes, from which the relevant spectroscopic information is obtained. Beta-, proton-, and alpha-delayed gamma emission are the most common examples. Close to the driplines, where the Q -values for decay are large and the particle-break-up thresholds of the daughter nuclei are low, delayed emission of ions also becomes possible, if not prevalent. Detection of prompt and delayed charged particles is therefore very important.

The direct *implantation* of the radioactive species of interest in a segmented charged-particle detector offers several advantages. Contrary to the case where detectors are placed *close to* the source of the decay activity, with the implantation method the efficiency for the detection of the decay events is only limited by the possible dead time of the acquisition system and can be determined accurately; this allows a precise normalization for the branching ratios of the various decay channels. The identification of a decay channel is based on the spectrum of the emitted particles, on the timing behaviour of the radiation, and on correlations between the implantation signal, the decay signature, and possible further signals from daughter-decay. The sum spectrum of the emitted charged particles can be measured avoiding distortions due to energy-loss effects; if desirable, the signal due to beta particles can be minimized by using a small size for the detection element (segment, pixel), in which electrons would deposit only a very small energy. Ancillary detectors for beta and gamma radiation can be added to the set-up. Both time and position correlations can be applied: the latter is based on the segmentation of the detector, as the emitted ions and the daughter nuclei remain well-localized in the detection element where the mother nucleus was implanted. Time correlations are made acquiring a time stamp for each event. In this respect, it has been shown that, by using a new beta-gamma decay spectrometer based on segmented germanium detectors and an event-by-event acquisition system initially developed for the MINIBALL set-up, identification of long-living isomers was possible through the analysis of large time-base correlations. The analysis technique was applied to beta-gamma coincidences, but it is not dependent on the kind of radiation signal.

For the implantation technique, the initial nuclei need to have a large velocity, in order to be placed sufficiently deep in the detector, where the light ions emitted in the decay would not escape. The method is thus often employed as tagging for reaction products, including nuclei produced by the in-flight separation technique. At HIE-ISOLDE, the post-accelerated beams can be directly implanted in the segmented detector. The superior characteristics that the ISOL beams offer give several advantages: a precise energy definition, resulting in a well-defined implantation depth that strongly reduces uncertainties due to escape decay events; high purity and intensity, allowing a precise normalization and thus detailed spectroscopy of nuclei very far from stability, including the study of extremely weak and exotic decay channels.

3.5 Reaction studies

3.5.1 Transfer reactions near the driplines

Transfer reactions for stable nuclei and their neighbours have already been studied in detail, see, for example, [Tsa05, Lee07] for an overview of results of (p,d) and (d,p) reactions in light nuclei. Acceleration of ISOL beams, as done in REX-ISOLDE, now gives the possibility of also exploring nuclei closer to the driplines and in the most extreme cases to go beyond the dripline to unbound nuclei. First experiments in this direction have already been performed, the example we shall use here being the investigation of the ${}^9\text{Li}+d$ reaction performed just after the completion of the accelerator [Jep05, Jep06]. The improvements possible with HIE-ISOLDE will be illustrated with this type of experiment.

These experiments will, of course, benefit from the energy upgrade of the REX-LINAC to at least 5.5 MeV/u, since the accessible excitation energy window in the probed nucleus would be increased as well as the c.m. angular coverage in cases where the light fragment is identified in a telescope structure (see Figure 3.14 where the angles are taken with respect to the incoming beam, so that 180 degrees corresponds to maximum transfer cross-section). Furthermore, an increase in the beam energy would diminish the contribution from Rutherford scattering, since the cross-section is proportional to $1/(E_{\text{c.m.}})^2$ and allows for larger beam currents when the count rate is an issue. Finally, calculations indicate that the overall transfer cross-section for radioactive nuclei has a maximum of around 3–5 MeV/u compared to 6–8 MeV/u for stable nuclei [Len98]. An upgrade to 5.5 MeV/u beam energy would in many cases, therefore, suffice for the very shortlived nuclei. However, it would still be interesting to study reactions up to about 10 MeV/u, partly to test the theoretical predictions of the beam energy dependence (believed to be coupled to the structure of the nuclei), and partly to access higher excitation energies in the produced nuclei.

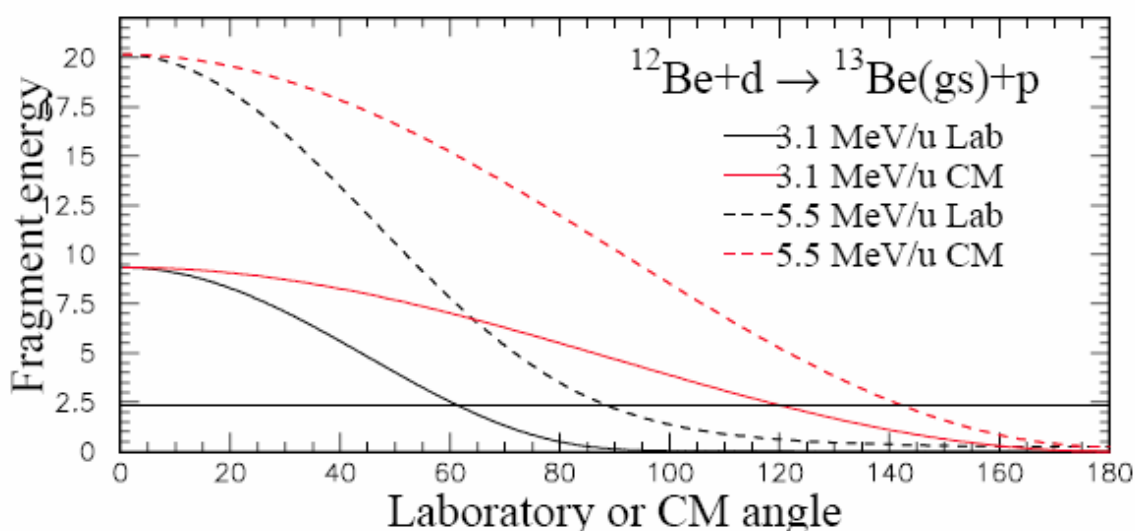


Figure 3.14: Simulation showing the increase in accessible c.m. angular range when going to higher beam energy. The horizontal line indicates the identification threshold for protons in a standard DSSSD telescope, see, for example, [Jep05, Jep06].

With the increase in beam intensity foreseen at HIE-ISOLDE, a more flexible bunch structure of the beam, in particular longer EBIS pulses, would be very valuable. The present bunch length of up to 50 μs gives a rather high instantaneous beam intensity putting severe demands on the DAQ system. To give an idea of the order of magnitude, with the target thicknesses employed so far, one recorded reaction per EBIS pulse corresponds roughly to 10^6 ions per second incident on the reaction target. The possibility of stretching the EBIS pulse to several 100 μs would relax the requirements on the DAQ system, thus allowing one to run with the higher beam intensities that will be available for many isotopes at HIE-ISOLDE.

One should stress here that a continuous beam would probably not be advantageous, since the bunched structure reduces significantly the background from the subsequent decay of scattered beam which is stopped in the chamber. Furthermore, the structure of the decay background can be identified by measurements in the time between EBIS pulses. With the present time structure (50 μs pulses at 50 Hz) the background is suppressed by a factor of a thousand.

For very short-lived isotopes (less than 50 ms) synchronization of the EBIS extraction and the arrival of the proton pulse could be advantageous, as this could be used to minimize the decay loss.

Purity of the re-accelerated beams

One of the main problems at the present REX-ISOLDE facility is the beam purity after acceleration, where large stable backgrounds can be present at specific A/Q -values. These stable contaminants arise from either the buffer gas in REX-TRAP, which can be avoided to some extent by choosing a proper buffer gas for a specific wanted radioactive beam, or from rest gas in the EBIS, where the main contaminants are ^{12}C , $^{16,18}\text{O}$ and ^{14}N . This could be solved partly by improving the vacuum in the EBIS, but would not remove the very intense contaminant beams such as $^{12}\text{C}^{4+}$ (10^8 per second) which at present inhibit the use of beams such as $^{12}\text{Be}^{4+}$, $^9\text{C}^{3+}$ and $^9\text{Li}^{3+}$. We shall use the latter to illustrate the problem: at the moment one must use $^9\text{Li}^{2+}$ which is accelerated less efficiently, only to 2.8 MeV/u at present.

A way of improving the beam purity is to introduce carbon foils before the last bending magnet to strip the ions into higher charge states. Currently one carbon foil can be introduced into the beam, but unfortunately this is not sufficient in the case of $^9\text{Li}^{3+}$, for example, since the $^{12}\text{C}^{4+}$ will still dominate by more than two orders of magnitude. The fraction of ^{12}C remaining in the 4+ state is 0.3 % at 3.1 MeV/u and will go down by one order of magnitude to 0.04 % at 5.5 MeV/u, which is still insufficient to use ^9Li in the 3+ state. Introducing a second stripping foil one would enable twice the reduction if a mass separation of the beam after each stripping foil were possible. A possible alternative solution is to place the first foil before the last acceleration cavity, where only the ‘correctly’ charged ions would be accelerated to the correct energy, before impinging onto the second stripping foil in front of a bending magnet. Of course it would be better to have two bending magnets or, in a future extension, an energy focusing storage ring where the ions could be passed through the stripping foil as many times as needed to obtain the required beam purity.

For proton-rich nuclei, beam purity could also be insured by charge breeding to a high charge state ($A/Q < 2$) which would be inaccessible for stable nuclei, e.g., $^9\text{C}^{5+}$ which would have no possible contaminants. Unfortunately, this is not possible with the present Linac which can only accelerate nuclei with A/Q between 3 and 4.5. The flexibility to accelerate all ions with $A/Q < 4.5$ might be achievable within the superconducting Linac scenario or, if we consider charge breeding to normal A/Q values and stripping to lower values later in the acceleration sequence, if the later part of the beam line is dimensioned to handle also low A/Q values. Such developments would allow for a background-free systematic study of many proton-rich nuclei near the dripline either via proton elastic resonance scattering or transfer reactions of the type ($^3\text{He},p$), ($^6\text{Li},p$) and ($^3\text{He},^4\text{He}$).

Let us turn now to the requirements on variability of the beam energy; for most transfer reactions a full flexibility of the beam energy would probably not be necessary, but a number of discreet energies would be beneficial, e.g., with 0.5 MeV/u steps from 1.0 to 3.0 MeV/u plus 4.0 and 5.5 MeV/u as possibilities with similar step sizes if the beam energy is extended above this range. For elastic resonance experiments, with the present variation in beam energy when passing the reaction targets it is not imperative to be able to tune the beam energy in finer steps, but with further improvement in beam intensity (requiring the beam to exit the reaction chamber) and for experiments looking at states in heavier nuclei the situation could change. From already approved experiments we see in some cases, e.g., elastic scattering of ^{11}Be (IS444), that the beam energy needs to be tuned to specific energies. Also, if astrophysical reactions are to be investigated at ISOLDE it is likely there will be several

that will benefit from having flexibility in specifying the beam energy or from scanning the beam energy in a specific range.

Higher beam intensities would, of course, always be appreciated and in the few cases where the reaction rate is already at the limit of the DAQ system's capabilities the extension of the EBIS pulse, mentioned earlier, could solve the problem or thinner reaction targets could be employed; targets are currently fairly thick in order to increase the reaction rate. In cases where the present intensities are marginal, an increase in the overall beam intensities would open up the possibility of performing for transfer reactions or, at least, elastic resonance scattering. One such example is the transfer reaction $^{12}\text{Be}+d$, where a two orders of magnitude increase would be needed (this particular reaction also requires that the ^{12}C contamination be removed and would benefit from having synchronized the EBIS pulse and proton impact on production target).

The availability of beams of most elements up to Ne (C, N and O are the ones where beam developments would be very welcome) will clearly expand the physics possibilities at REX-ISOLDE, since the topics outlined above and so far limited experimentally to He, Li and Be beams could be investigated also in a slightly higher mass range.

We would like to point out also that once the HIE-ISOLDE goals have been achieved, one should explore the possibility of having polarized beams (see Section 3.3 for an explanation of the tilted foil technique). To take full experimental advantage of polarized beams will require quite intense beams, but it would bring in spin degrees of freedom much more directly and would allow for a new level of studies of exotic beams.

3.5.2 Two-body reaction experiments in heavier nuclei

In order to make precise tests of the nuclear wavefunction, well-established techniques for gaining quantitative information about the excited states of an atomic nucleus can be employed: **Coulomb excitation** and **few-nucleon transfer**. The former probes mainly the collective degrees of freedom, while the latter gives information on the occupation of single-particle states. These well-known techniques can be employed on exotic nuclei because of the emerging availability of accelerated radioactive beams at REX-ISOLDE.

Coulomb excitation

Coulomb excitation, an electromagnetic probe, is readily used to study collective behaviour but also supplies interesting information on single-particle properties of atomic nuclei. The evolution of shapes and shells in exotic nuclei can be uniquely studied in series of measurements along isotopic chains revealing, for example, transition matrix elements and quadrupole moments that can be directly compared to theoretical predictions. The high quality of the REX-ISOLDE post-accelerated beams has allowed over the last five years a series of pioneering Coulomb excitation experiments in inverse kinematics [Ced07, Hur07, Nie05, Ste07]. The combination of the efficient and highly segmented MINIBALL germanium array and its ancillary detectors with the ISOLDE beams has resulted in successful measurements with beams covering a large part of the nuclear chart from ^{32}Mg , ^{70}Se , ^{80}Zn , ^{106}Sn to the heavy beams around ^{142}Xe . These campaigns addressed a rich physics spectrum from the evolution of the shell structure far from stability to the onset of deformation away from closed shells and along the $N = Z$ line. The wide variety of purified beams, unique world-wide, from ISOLDE that are efficiently post-accelerated with REX has allowed studies of nuclei far-from-stability with half-lives well below a second (e.g., $T_{1/2} (^{32}\text{Mg}) = 0.12 \text{ s}$). Experiments

were performed with beam intensities as low as a few thousand per second because of the high efficiency of the detection system. Crucial in this respect was the purity of the radioactive ion beams whereby the unique expertise present at the ISOLDE facility in resonant laser ionization sources and molecular beam techniques is essential. It is noteworthy that low-energy transitions could also be clearly resolved, see, for example, Figure 2.5, in contrast to the typical situation at in-flight facilities where a large atomic background is present. This is important both for investigations of heavy deformed nuclei and of odd- A and odd-odd nuclei.

Currently, the final energy of the REX accelerator (3 MeV/u) limits the possibilities. An increase to > 5 MeV/u for the HIE-ISOLDE facility in combination with an upgrade of the injection system will open a new window of opportunity. Substantially higher count rates for one-step Coulomb excitation and for multiple-step Coulomb excitation can be obtained. For isotopes with a high-lying first excited state (situated mainly around closed shells), such as ^{68}Ni , an order of magnitude in count rate will be achieved when going from 3 to 5 MeV/u; in the case of ^{68}Ni a factor of 40. The recently demonstrated feasibility to accelerate beams of mass up to 200, unmatched by any other radioactive beam facility worldwide, and the Coulomb excitation experiment on $^{184-188}\text{Hg}$ has opened up a new, vast area for exploration that requires higher energies than available at present. This is illustrated in Figure 2.8 where the Coulex cross-section for ^{182}Hg is shown as a function of the beam energy.

Few-nucleon transfer reactions

Historically, few-nucleon transfer reactions have been an important tool for the investigation of nuclei at or near stability and of the single-particle properties of nuclear states such as their energies, spins, parity, as well as occupation probabilities. Therefore, few-nucleon transfer reactions have played a major role in establishing the shell model picture of near closed-shell nuclei. Furthermore, two-nucleon transfer reactions have been successfully used to investigate nuclear pairing as well as shape coexistence and shape transition phenomena. In nuclei further away from stability such reaction studies could not be used in the past as no targets could be produced from short-lived nuclei. With the advent of re-accelerated beams of short-lived ions few-nucleon transfer experiments became possible again and will play a key role in testing the new theoretical predictions for the changes in shell structure far-off stability. For example, in the case of the fp shell, neutron transfer measurements on, for example, neutron-rich Ca isotopes, will allow sensitive quantitative tests using spectroscopic factors to be made.

For transfer reactions with nuclei far off stability it is necessary, owing to the short half-lives of the nuclei of interest, to perform the reaction in inverse kinematics with a heavy-ion beam impinging on a target containing light ions. Typical targets include deuterated polyethylene foils for (d,p), or tritium-loaded titanium foils for (t,p) reactions. Also the use of a Be target for single neutron (^9Be , 2α) or two-neutron (^{10}Be , 2α) reactions is possible where the detection of the 2α breakup of the residual ^8Be nucleus serves as unique reaction trigger. For proton transfer reactions liquid He targets would be needed. In all these reactions spectroscopic information on the populated levels can only be obtained by detecting the light target like particles, such as protons or alphas, in a detector array surrounding the target. However, owing to effects of target thickness, beam spot size, and finite opening angle for the charged particle detectors, the obtainable energy resolution is much more limited as compared to charged particle spectroscopy with a high-resolution magnetic spectrograph, such as a Q3D. For example, typical values for the resolution in excitation energy are at least 140 keV for (d,p) reactions near the Coulomb barrier while 5 keV resolution has been achieved for protons at the Munich Q3D. The resolution can be regained by combining charged-particle

detection in a large-solid-angle detector system as shown in Figure 3.15 with high-resolution gamma-ray spectroscopy employing segmented germanium detectors, such as MINIBALL.

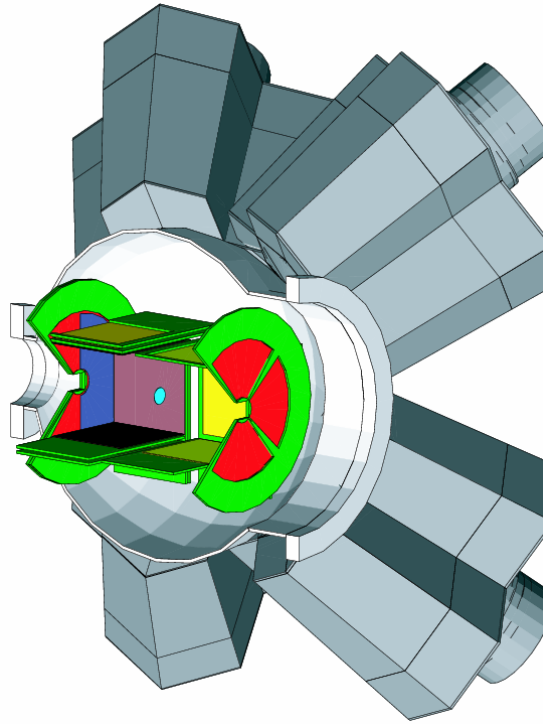


Figure 3.15: Sketch of the large-solid-angle detector system TRACE, based on position-sensitive double-sided silicon strip detectors, for the detection of charged particles at the MINIBALL target

As pointed out by Lenske and Schrieder [Len98], cross-sections for transfer reactions in inverse kinematics show a maximum at low energies, providing the opportunity for REX-ISOLDE to make major contributions in the study of single-particle structure far off stability. For light projectile nuclei the cross-section maximum is found near 2–3 MeV/u, while it is around 5 MeV/u for mass 130 nuclei. Because of the large impact parameter at which these reactions occur, such low-energy reactions are very useful tools to study the tail of the single-particle wave-functions in particular for weakly bound systems. At the same time the low reaction energies result in very smeared out or shallow angular distributions, which makes it difficult to uniquely determine the transferred angular momentum, in particular when $l = 3$ or 4 orbitals are involved. High-angular momentum orbitals are also best populated in mismatched reaction with high Q -value, such as (α, t) reactions. Altogether, it is therefore important to find the optimum beam energy for which a given experiment can be performed with the low beam intensity of the radioactive beam so that critical properties, such as the transferred angular momentum, can be deduced uniquely. Since this compromise depends on the individual experiment, a large range of available energies between 2 and 10 MeV/u seems most appropriate. Since there is no prompt gamma-emission from the ground state or long-lived isomeric states it is important to add an appropriate large acceptance but high resolution recoil spectrometer behind the MINIBALL target. This is also essential for the reduction of charged-particle background from fusion reactions of the beam with the target carrier material, such as C or Ti and the like.

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Annex: Estimated beam intensities for HIE-ISOLDE

Introduction

The yields of radioactive isotopes at an ISOL facility depend on many parameters, several of them target specific, see for example [Rav94]. The existing ISOLDE yield database [YDB] contains experimental information from many years of target-ion source operation and allows a reliable estimate to be made for the yields that will be available at HIE-ISOLDE, see Chapter 3 in [HIE06]. The present annex will focus on the intensities of postaccelerated beams available at REX where several factors affect the final intensity; in contrast the intensities of low-energy beams are expected to increase by a factor of about 3 owing to the increase of primary proton beam intensity. Some target designs may not stand the increased load from the primary beam, similar to the situation today for liquid metal targets, but one should note that the estimates presented here are in general conservative in the sense that they neglect future improvements in target and ion source technology. Present yields at PSB-ISOLDE are the result of more than 40 years of beam development, and foreseen developments, such as those that will come from the upgraded RILIS ion source, will improve the situation further. The physicist planning an experiment will, apart from the yield information, need to know the purity of the specific beam of interest and will be required to take the necessary safety precautions for handling the beams. Note that the techniques for beam purification are continuously being improved and also form part of the HIE-ISOLDE project; one of the not yet fully explored methods is in-trap purification. As at the present ISOLDE facility, users will be encouraged to contact the technical group to clarify these and any other questions they may have.

The individual upgrade components are described in detail in the technical report [HIE06]. The average proton current will increase from the present 1.9 μA to 6.4 μA because of the decreased repetition time of the PS Booster and the introduction of Linac4. The present yields [YDB] will be assumed to scale linearly with this increase. The intensity of the postaccelerated beams is affected by the efficiency of the low-energy stage (REXTRAP and REXEBIS) and the Linac efficiency. The currently obtained intensities are given in [Vou]. The Linac efficiency is taken as 80% and the efficiency of the low-energy stage is interpolated from the currently obtained values as measured with radioactive beams and shown in Figure A.1.

The space charge limit of REXTRAP is around 10^8 ions per bunch and the throughput will therefore be limited for intense radioactive beams with long breeding times. The RFQ cooler may overcome this bottleneck by taking over the bunching role of REXTRAP, but there are not yet sufficient data to evaluate this possibility quantitatively. An alternative solution is to employ the PHOENIX ECR charge breeder for the most intense beams, its measured efficiency [Del06] is given in Figure A.2.

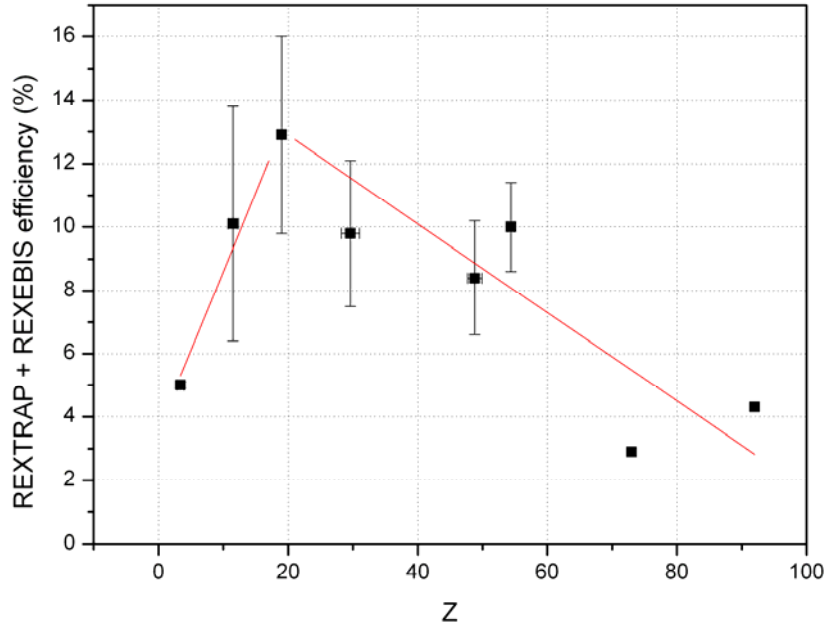


Figure A.1: Efficiency of REXTRAP and REXEBIS for charge breeding into an appropriate charge state measured with radioactive beams

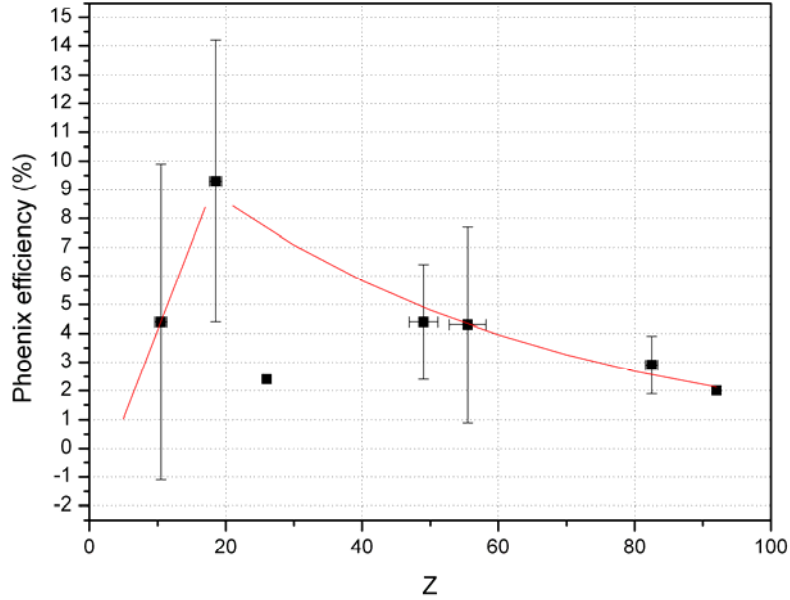


Figure A.2: Efficiency of charge breeding of the PHOENIX ECR measured with stable beams

The breeding time is important for the overall throughput and will also give decay losses for short-lived isotopes. For a nucleus with half-life $T_{1/2}$ and a breeding time T_b the transmitted fraction will be $\exp(-\ln(2)2T_b/T_{1/2})$, since the total preparation time in REXTRAP and REXEBIS is twice the breeding time. The proposed upgrade of the REXEBIS will shorten the current breeding times, shown in Figure A.3, by a factor of four. The values used later are obtained by interpolation. For the PHOENIX ECR a fixed breeding time of 200 ms is assumed.

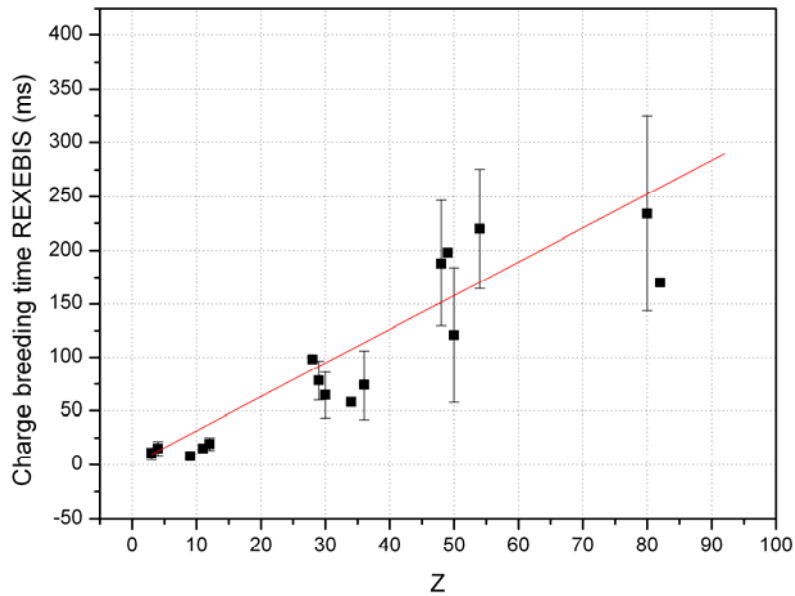


Figure A.3: The currently measured REXEBIS breeding time given as a function of the element number Z

Estimated beam intensities

The ISOLDE yield database contains information on more than 800 isotopes; only a selection of these will be included here to illustrate the expected conditions at the upgraded REX-ISOLDE. The estimated beam intensities are based on experimental yields mainly taken at the present ISOLDE facility located at the PS Booster, except for those of the element Cs which were taken at the former SC-ISOLDE. For the elements In and Rn yields measured at the PS Booster have been supplemented by (scaled) yields as measured from SC-ISOLDE. Filled symbols were obtained assuming charge breeding in REXEBIS and open symbols in PHOENIX ECR; the exact conditions where one would change from operation of one device to the other have not yet been determined. The lines in Figures A.4 to A.8 are included to guide the eye. Only intensities for nuclei in their ground state are reported; the intensities for isomeric states are known in many cases and can be found in the ISOLDE yield database. Acceleration of selectively ionized isomers or ground states has already been pioneered at the present facility.

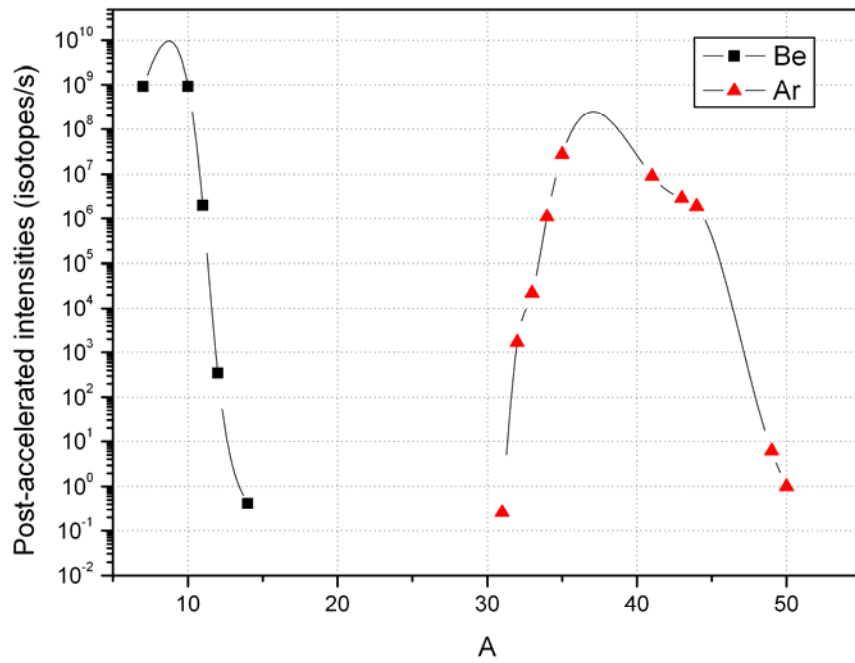


Figure A.4: Estimated intensities for accelerated beams of Be and Ar

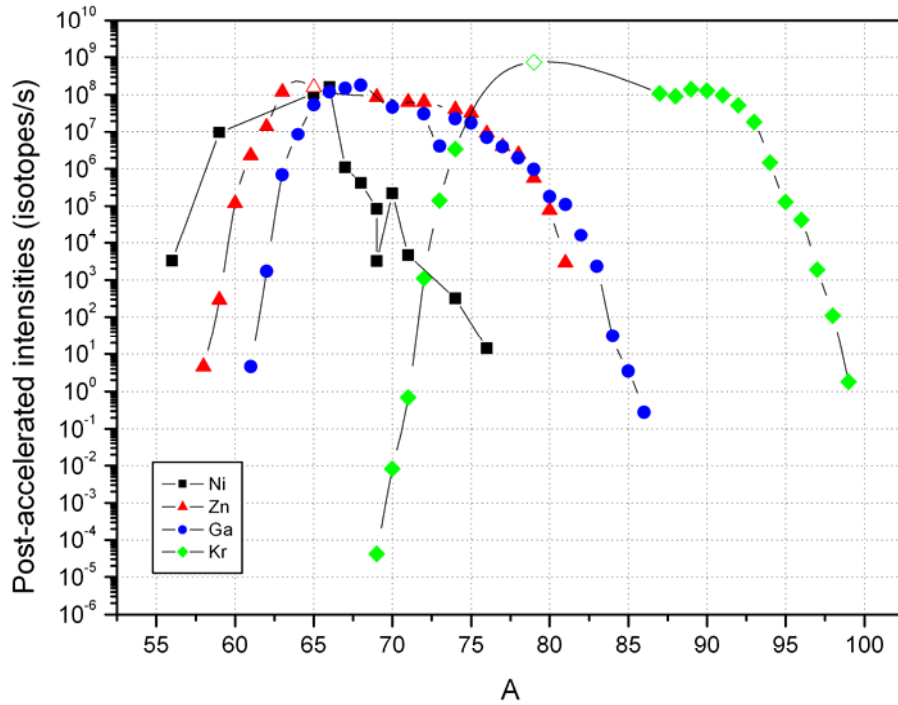


Figure A.5: Estimated intensities for accelerated beams of Ni, Zn, Ga and Kr

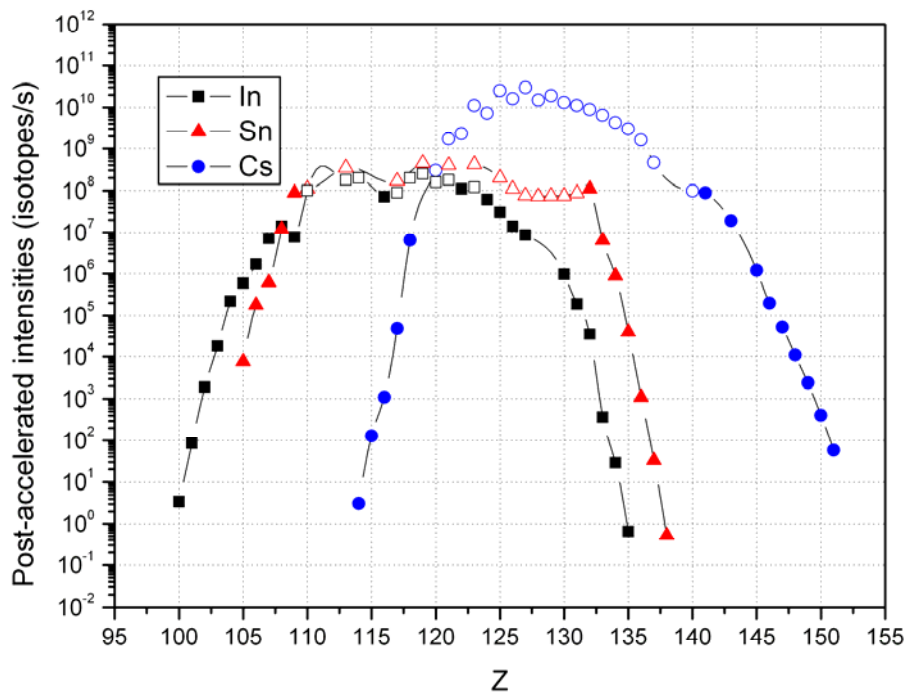


Figure A.6: Estimated intensities for accelerated beams of In, Sn and Cs

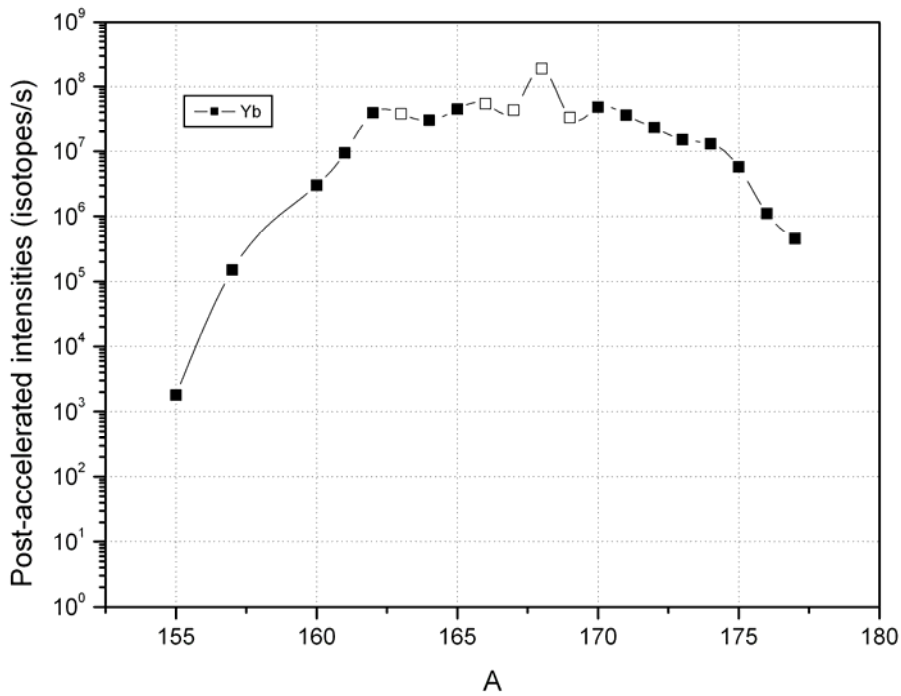


Figure A.7: Estimated intensities for accelerated beams of Yb

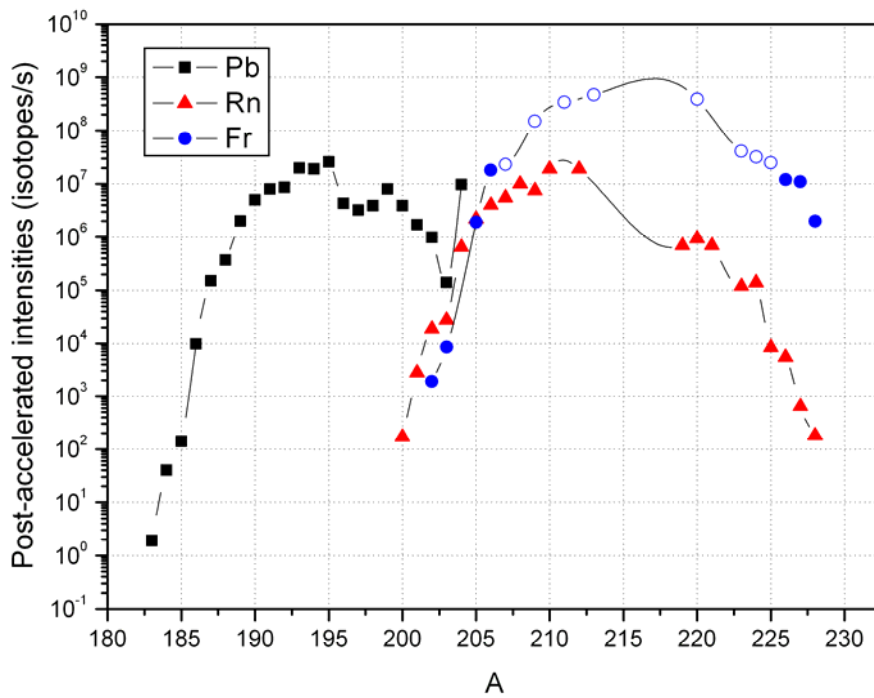


Figure A.8: Estimated intensities for accelerated beams of Pb, Rn and Fr

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