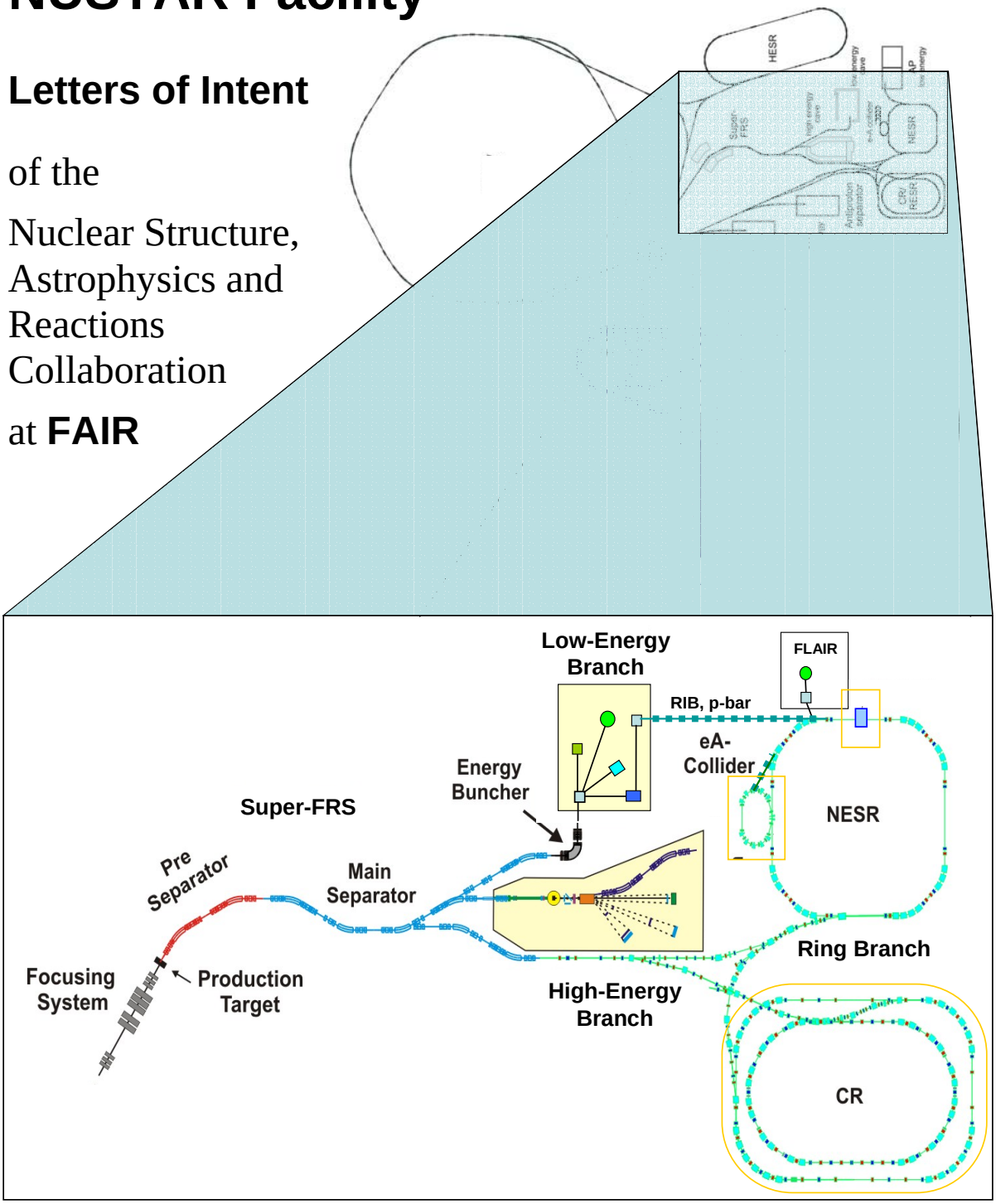
NUSTAR Facility

Letters of Intent

of the

Nuclear Structure, Astrophysics and Reactions Collaboration

at **FAIR**



April 2004

Content

1. Introduction

The ability to produce beams of unstable nuclei has transformed nuclear science. It opens the exciting prospect of being able to study in detail the properties of nuclei very far from the valley of stability. The resulting extension in our knowledge will pose a considerable challenge to our present theoretical understanding of the nuclear many-body system. Such studies will allow us to address a large range of essential questions concerning ***nuclear structure and dynamics***, ***nuclear astrophysics***, ***tests of fundamental interactions and symmetries as well as new applications in different fields***. Despite the variety of individual questions addressed, there are a few encompassing themes related to the challenges facing modern science at large and they connect this field to many other areas of science. Because nuclear science is linked by these overarching themes as well as a common infrastructure the community planning to use the beams of exotic nuclei provided at the International Facility for Antiproton and Ion Research (FAIR) at Darmstadt has formed the NUclear STructure, Astrophysics, and Reaction (NUSTAR) collaboration at FAIR to pursue the common goal of an ideal facility for this research.

This introductory section will adumbrate the encompassing themes as well as highlight some of the more specific questions to be addressed. A much more complete discussion of the NUSTAR physics can be found in the Conceptual Design Report for the FAIR project. This document will also briefly describe key experiments and methods using the beams of exotic nuclei produced and separated at the Super-conducting Fragment Separator (Super-FRS) to achieve the major goals of the NUSTAR physics programme. In doing so, it will become apparent that it is of key importance to use a variety of experimental techniques to shed light on different aspects of the structure and dynamics of exotic nuclei and the interplay of fundamental interactions.

Following this introduction the Super-FRS itself will be described in some more detail. If theoretical concepts are to be developed to achieve an understanding of the new data to be harvested on exotic nuclei, a coherent effort is required. To this end a theory network will be organised and its aims and objectives are introduced in the subsequent chapter. The main body of the document follows and consists of the individual letters of intent for experimental set-ups constituting the NUSTAR facility, which are grouped by the three branches of the Super-FRS.

1.1 The intellectual challenges and goals of NUSTAR physics

The study of the atomic nucleus, core of the atom and carrier of essentially all visible mass in the Universe, has undergone a major re-orientation in the last decade and has seen the emergence of new frontiers. In particular the availability of energetic beams of short-lived (radioactive) nuclei, in the following referred to as rare isotopes or exotic nuclear beams, has opened the way for the exploration of the structure and dynamics of complex nuclei in regions far away from stability, where very limited information is available. Among the harbingers of the exciting new topics emerging from this research are, for example, the appearance of single- and double-nucleon (Borromean) halo nuclei as well as the breakdown of the magic numbers, the long-standing benchmark for structural evolution. The new facility together with the experiments proposed in the individual letters of intent will provide the tools for a far-reaching, in-depth exploration of this new frontier. Due to the prospect of beam intensities increased by a factor of up to 10,000 at the NUSTAR facility compared to the current FRS at GSI, one expects a much broader range of new phenomena to emerge in the region beyond the present limit of experimental accessibility.

Nuclear structure and dynamics

The atomic nucleus is a finite, 2-component (protons and neutrons) many-body system, whose structure is most decisively governed by the strong force. Significant advances have been made in the theoretical modelling of nuclear structure, from *'ab inito'* calculations of few-nucleon systems, based on bare nucleon-nucleon interactions, to various shell model methods using sophisticated truncation schemes, and mean-field methods using density functional theory. It is a major aim of nuclear theory to explore connections between these descriptions in order ***to develop a unified description of the nucleus***. Within this context it is also of great importance to develop new methods to tackle the description of nuclei far away from stability where completely new and exciting phenomena are to be explored. It is a fascinating challenge to develop a complete understanding of ***how this complex many-body system is built from***

simple ingredients. Studies of atomic nuclei are thus intimately linked with those on fundamental interactions and on sub-nucleonic degrees of freedom.

The atomic nucleus displays many astonishing regularities and simple excitation patterns. The reason for the ***emergence of regularities and simple modes*** of excitation is connected to the fundamental role of symmetries for the structure and dynamics of the nuclear many-body system. At the ***limits of nuclear existence***, in particular near the driplines, different symmetries and structural paradigms may be found.

The structure and dynamics of loosely bound nuclei near the driplines is very different from that of stable nuclei. Rather diffuse surface zones, so called ***halos and skins***, have been observed in light neutron-rich exotic nuclei. Among other features unique to such nuclei, one expects to encounter novel types of shell structures, new collective modes, new isospin pairing phases, possible new decay modes (e.g. double proton emission) or regions of nuclei with special deformations and symmetries. The effects of nucleonic clustering should become more prominent, giving rise to unusual nuclear properties.

Theoretical concepts have to be developed further in order to achieve a profound understanding of the expected new data on exotic nuclei. Outstanding problems are the appropriate effective interactions in new regions of density and isospin, many-body methods that account for the weakness of the mean field, as well as structure and reaction models that can cope with the continuum in close vicinity to bound states.

During the past decade it has been demonstrated that reactions with high-energy secondary beams are an important tool for the exploration of the properties of nuclei far off stability. A comprehensive reaction theory for such experiments is an essential prerequisite for the extraction of detailed spectroscopic information, in particular for reactions with weakly bound nuclei.

Exotic neutron-rich nuclei. The NUSTAR facility will give access to the neutron drip line up to about Z=25, thus greatly extending the current knowledge from the present limit of Z=8. In heavier nuclei, though the dripline cannot be reached, the isospin dependence of nuclear structure phenomena can be studied and weaker binding is expected to bring about extended surface zones of neutron-enriched low-density matter. The study of these neutron skins or halos determines the effective interactions in such nuclear environments and thus may help to investigate the equation-of-state of cold neutron matter between saturation and low density. Among the loosely bound valence nucleons, residual interactions such as pairing become enhanced and may produce cluster and molecular-type structures. Investigations of the most neutron-rich isotopes offer direct access to part of the r-process path, leading to a fruitful synergy of nuclear structure and nuclear astrophysics.

Single-particle and collective degrees of freedom. The long established magic numbers of nuclear shell structure are not valid globally but are modified significantly by residual interactions, which in turn depend on the occupation of specific single-particle orbitals. At the same time the weaker binding in very neutron-rich nuclei may lead to a more diffuse mean field and a modified spin-orbit interaction, all of which lead to a modification of the shell gaps. Such modifications of shell structure have an influence on the evolution of nuclear shapes and collective modes. The NUSTAR facility will permit detailed studies of nuclear shell effects and nuclear shapes. Extended, hitherto unexplored regions of neutron-rich nuclei, e.g., below lead, will be accessible via uranium fission and fragmentation. The combination of direct mass measurements in a storage ring to explore the nuclear mass surface and detailed spectroscopy of particularly interesting regions with the new generation of efficient detector arrays for particle and gamma-ray spectroscopy will lead to a new and exciting research programme.

Proton drip line and N = Z nuclei. Nuclei near the proton drip line could be studied in the past by using reactions between stable beams and targets. Neutron deficient nuclei are thus much better explored than neutron-rich ones. The heaviest self-conjugate nucleus ^{100}Sn was observed at the exotic-nuclear-beam facilities, GSI and GANIL. Nuclei at or near the symmetry line at N = Z are of particular interest in many respects. They are the micro-laboratory for high-precision tests of the Standard Model and they are found along the astrophysical rp-process path. Nuclear physics interests focus on isospin-symmetry breaking effects in heavy nuclei, on the open question of a proton-neutron pairing phase as well as the study of rare decay modes, such as the recently observed two-proton radioactivity.

Nuclear reactions at the highest energies. The dynamical properties of the two-component nuclear matter can be studied in nuclear reactions at high energies, i.e., fission, spallation, fragmentation, as well

as multifragmentation. Extreme deformation, nuclear matter at low densities and finite temperature, or the nuclear equation-of-state and their isospin dependence can be investigated at the NUSTAR facility. A detailed understanding of the spallation reaction mechanisms is also important for applications, e.g., for radioactive beam production or for the design of neutron sources.

The NUSTAR facility will allow the extraction of the basic properties of nuclei at the extremes of nuclear existence while at the same time allowing in-depth investigations of exotic nuclei closer to stability Exploring nuclear structure and nuclear stability under extreme conditions is essential for a comprehensive understanding of the nuclear many-body system. It is also the basis for understanding the various aspects of nuclear astrophysics and for many applications of nuclear physics.

Nuclear Astrophysics

All atomic nuclei in the Universe beyond lithium have been and still are being created in stars. In various stellar environments this ***'nucleosynthesis'*** proceeds via the formation of transient nuclei that decay into stable ones, either directly or after several intermediate steps. The remnants of these processes are dispersed into interstellar space in the death throes of stars. Eventually the gas and dust, of which they form a part, will contract and serve as the seeds for a new generation of stars and their companions, such as our Sun and the Earth.

In order to understand the formation, evolution, and final fate of stars, and to determine the stellar sites, pathways, and time scales involved in the synthesis of the elements, astrophysicists and nuclear physicists work closely together. Astrophysics defines possible stellar scenarios in terms of temperature, density, pressure and chemical composition, and nuclear physics supplies fundamental characteristics, such as masses, half-lives as well as reaction rates of key nuclei participating in the complex steps of nucleosynthesis. However, just as stellar scenarios might depend on nuclear structure, nuclear properties may be altered in different stellar environments. The actual pathways of nucleosynthesis can be drawn only by a careful analysis of the data from both disciplines.

Light and medium-heavy elements are produced by nuclear fusion in the hot and dense cores of stars. This process ceases with the element iron since fusion to heavier nuclei would require the input of energy. As a result medium-sized stars burn out after this stage has been reached. Only in very massive stars the creation of heavy atomic nuclei proceed further on the neutron-rich side, by the interplay of neutron capture and beta decay. The stable, heavy and neutron-rich atomic nuclei found in our solar system have been produced in at least two processes. The slow neutron capture process (***s-process***), creating nuclei close to the valley of beta-stability, is believed to be largely understood. Most of the heavy atomic nuclei, however, originate from an explosive process of nucleosynthesis, the so-called rapid neutron capture process (***r-process***). The stellar site of the r-process is still uncertain and just as little is known about the detailed path of the r-process, due to a lack of precise nuclear data in this region. A major goal of the NUSTAR facility at FAIR is to enable the measurement of masses and half-lives of nuclei near the N=126 closed neutron shell, in order to address experimentally for the first time the way the heaviest elements have been created.

Neutron-deficient nuclei close to the proton drip-line are produced in other explosive scenarios, such as novae explosions or X-ray bursts. In these processes, hydrogen is burned explosively through a sequence of rapid proton captures (***rp-process***) and beta-plus decay. Many important questions concerning the rp-process will be addressed using the exotic nuclear beams of the NUSTAR facility.

Experiments based on the new generation of exotic nuclear beams will mean a major step forward in the field of nuclear astrophysics by providing essential properties such as masses, lifetimes, and reaction rates for key nuclei far from the valley of stability. These data are the basic ingredients for understanding the intricate details of nucleosynthesis, the evolution and fate of the stars and finally the abundance of the elements in our solar systems, our galaxy, and in the Universe.

Fundamental Interactions and Symmetries

The Standard Model of Elementary Particle Physics summarizes our present knowledge on the fundamental building blocks of matter – the quarks and the leptons – and their interactions via exchange particles (so-called gauge bosons). It describes the electromagnetic, the weak and the strong force, and the fundamental symmetries (or symmetry violations) underlying these forces. The Standard Model has

withstood three decades of extensive experimental scrutiny. Despite its great success, most physicists are convinced that the Standard Model eventually needs to be replaced or at least extended. Low-energy precision experiments in nuclear and atomic physics show a unique discovery potential for this field. The major thrust of the nuclear physics studies focuses on the weak interaction, in particular on precision experiments of the beta-decay of specific exotic nuclei, emphasizing symmetry violation and the different interaction types of the weak force.

Such studies comprise precision tests of parity and time-reversal symmetry, of the conserved vector current (CVC) hypothesis, and sensitive searches for other than vector-axial vector (V-A) contributions to the weak interaction that would hint at the existence of additional exchange bosons of the weak interaction. In particular, the new NUSTAR facility would be uniquely suited to extend high-precision measurements of super-allowed $0^+ \rightarrow 0^+$ transitions significantly beyond the present limit of Z=27, probing the V_{ud} matrix element at the hadronic vertex of the weak interaction and, thus, the intensely discussed unitarity of the CKM (Cabibbo-Kobayashi-Maskawa) matrix.

The new facility will open a qualitatively and quantitatively new era, since the considerably increased production yields for exotic nuclei together with novel beam manipulation techniques, such as beam cooling, deceleration to rest and storage in ion or atom traps, will increase the precision achievable in these studies by one order of magnitude and more.

Relation to other research at FAIR

The NUSTAR activities (physics goals, instrumentation, and infrastructure) are connected to a number of other research activities planned at FAIR. An additional dimension of the chart of nuclides is spanned by hypernuclei, which contain strangeness as an additional quantum number. Antiproton beams at the proposed facility will allow efficient production of hypernuclei even with more than one strange hadron. The structure of hypernuclei will give an insight into the hyperon-nucleon interaction and thus will in turn further a better understanding of the nucleon-nucleon interaction.

The low energy precision experiments in nuclear physics are part of a larger effort to test fundamental interactions and symmetries at FAIR. Other experiments are planned using atomic physics techniques, as well as trapped and high energy antiprotons.

1.2 The experimental branches of the NUSTAR facility

The NUSTAR facility will consist of four basic components. The **Super-FRS** itself will provide beams of exotic nuclei produced in projectile fragmentation or in-flight fission. The secondary beams can be directed to three different experimental branches, which are equipped for a variety of experiments. The **High Energy Branch** will contain a complex detector set-up around a large-acceptance bending magnet for kinematically complete experiments on nuclear structure and reaction physics up to the highest available energies. The **Ring Branch** consists of a storage ring system in which ions can be stored and cooled for mass and half-life measurements as well as scattering experiments. Letters of intent for light ion reactions on a gas-jet target as well as schemes for an electron-nucleus collider and an antiproton-nucleus collider are part of this document. At the **Low Energy Branch** the high-energy beams are slowed down by an energy buncher system and are stopped in a gas cell for decay spectroscopy, for trap experiments, and laser spectroscopy. Alternatively, the low-energy beams can be directed to a dedicated set-up for spectroscopy and reaction studies, where detailed information on very short-lived nuclei can be obtained.

1.3 Opportunities and synergies at the NUSTAR facility

The experience of studying nuclei has clearly shown the importance of utilizing different experimental techniques to measure similar or related observables. Different probes and/or different beam energies are needed in order to optimize the sensitivity to particular nuclear structure observables. For example, different types of nuclear transitions can be selectively induced by means of a proper choice of the probe and momentum transfer. Here, the proposed experiments for the three branches complement each other in an ideal way. Complementary approaches are also asked for due to the fact that the production rates decrease rapidly with increasing neutron (proton) excess: While high-resolution experiments providing

detailed nuclear structure information will be possible at the NUSTAR facility for a wide range of radioactive nuclei which are presently not accessible, dedicated experiments are needed in addition providing high sensitivity to study the most exotic nuclei at the very limits of production rate.

As another example, one may point to the measurement of nuclear radii and density distributions. While rms-charge radii have been determined by means of laser spectroscopy, charge density distributions are determined from elastic scattering of electrons, and matter distributions can be obtained from elastic proton scattering. Thus the use of various techniques enables the determination of proton and neutron density distributions. This will become even more relevant for very neutron rich nuclei, where the density distributions for protons and neutrons are expected to be very different. Such studies will become possible for the first time by the combination of measurements at the internal target in the storage ring and the eA collider. A complementary approach is antiproton absorption as a tool to determine proton and neutron rms radii independently in the same experiment.

Usually the different experimental approaches, if available at all for radioactive nuclei, have been used at different accelerator facilities depending on the availabilities of beam particles and energies. The NUSTAR facility at FAIR will enable for the first time to perform such experiments at one facility, with great benefit for intellectual and technological synergy effects.

The NUSTAR facility will span the full range of experimental techniques needed to pursue the intellectual challenges outlined above, including novel experimental techniques not available at present for radioactive nuclei like, e.g., electron scattering off exotic nuclei. Hereafter it will be highlighted how the information on nuclear structure and dynamics as well as nuclear reactions can be obtained from the most basic ground state properties to in-depth spectroscopic information.

- The first property of an exotic nucleus that can be determined is the fact if it is bound or not against proton or neutron emission. This can be done with production rates as low as one per week at the Super-FRS.
- Measurement of half-lives and basic decay properties can be performed after implanting the nuclei into an active stopping detector with intensities of down to 10^{-3} per second. Such information is also very important for the determination of the complex path of nucleosynthesis.
- Measurement of nuclear masses down to single short-lived ions, with half-lives down to the microsecond range, can be performed over broader regions of nuclei using storage ring methods, while Penning traps will be used for high precision absolute reference masses.
- Astrophysically important reactions can be studied at the new facility in various ways. Neutron-capture rates, for example, can be measured directly using the proposed neutron capture set-up, or can be extracted from the inverse process using Coulomb break-up. Stored bare and few electron fragments as well as cooled isomeric beams allow to perform studies relevant to reactions in hot stellar plasmas.
- The size of the nucleus can be determined for the most exotic nuclei with production rates as low as one per second by measuring total interaction cross-sections. With more intense beams of exotic nuclei proton and neutron matter distributions can be determined using the combined information of elastic electron or proton scattering, antiproton-nucleus collisions, or laser spectroscopy. The latter two methods will only yield rms radii, while the scattering experiments can provide density distributions.
- Ground state magnetic and electric moments are accessible with laser spectroscopy while moments of excited states can be determined using particle gamma correlations in intermediate energy Coulomb excitation using the extremely high transient fields arising from the use of hydrogen-like ions.
- By using knockout or Coulomb break-up reactions at high energy it is possible to determine single-particle structure of the ground state. This is a particularly useful way to obtain information of very weakly bound nuclei, where due to the large cross sections experiments can be performed with beam intensities of a few particles per second only.
- The single-particle structure, as well as nucleon-nucleon and cluster correlations will be studied in quasi-free scattering experiments.
- Knowledge about excited states and their basic quantum numbers can be obtained using decay-spectroscopy of stopped nuclei as well as reactions such as knockout and secondary fragmentation.

- Transition matrix elements of the lowest excited collective states can be measured using Coulomb-excitation at intermediate energies with beams of 1000 pps.
- The study of giant resonances and low-lying collective modes provides essential nuclear structure information. While electric dipole resonances can be studied using relativistic Coulomb excitation with only 100 to 1000 pps, the monopole excitation, sensitive to the nuclear compressibility, is only accessible in (^{4}He,^{4}He') scattering in the storage ring. Dipole and Quadrupole modes are both accessible with the best resolution in inelastic electron scattering but also with inelastic alpha and proton scattering in the storage ring. Spin-isospin excitations, including the astrophysically important Gamow-Teller resonance, can be studied by charge-exchange reactions.
- Detailed particle and gamma-ray spectroscopy of stored and slowed beams using Coulomb excitation, transfer, fusion reaction, etc. will provide in-depth information on the structural evolution of nuclei in the intermediate region between the limits of existence and the valley of stability.
- The study of pionic states proposed for experiments with stored exotic nuclei provides a very sensitive tool to study the density dependence of the strong interaction as a function of isospin. Such experiments also investigate the mass modification and chiral symmetry restoration in the nucleus at zero temperature and nuclear densities.

Besides the physics complementarity of the proposed experiments, which will enable a broad and at the same time in-depth insight into the structure of exotic nuclei, there are a large amount of technological synergies in the proposed set-ups, which will be explored in order to make efficient use of available investment and effort. These synergies are also visible in the partial overlap in collaborations within the different letters of intent. Some of the planned common developments are listed hereafter.

- A common NUSTAR concept for data acquisition and front-end electronics will be developed, which is applicable to many detector set-ups and will be discussed in the section describing the Super-FRS.
- For all experiments high-rate, high-resolution tracking detectors are needed for unique event-by-event identification of secondary beams from shortly after the production target to the experiments as well as of heavy reaction products after secondary reactions.
- Several experiments in the Ring Branch need detectors that can operate under ultra-high vacuum conditions, which will be developed in a joint effort together also with other groups at FAIR.

In conclusion, the NUSTAR facility will enable worldwide unique experiments with the shortest lived exotic nuclei up to relativistic energies. The unique experiments possible at the NUSTAR facility include the electron-nucleus and antiproton-nucleus collisions storage ring experiments, reactions experiments at the highest energies providing clean access to the most exotic nuclei produced as well as complementary experiments with nuclei not accessible in ISOL facilities, namely refractory elements and nuclei with very short half-lives. The activities proposed within the NUSTAR letters of intent provide a coherent approach to the challenges of exploring the uncharted territory of nuclei far from stability. The diversity of the various experiments is essential to help answer fundamental questions concerning nuclear structure and dynamics, nuclear astrophysics, as well as tests of fundamental interactions and symmetries. We close with the 2004 NuPECC Long Range Plan, which points out that "With the experimental equipment available at low and high energy and at the New Experimental Storage Ring (NESR) with its internal targets and electron collider ring, the new facility will provide worldwide leadership in nuclear structure and nuclear astrophysics research."

Super-FRS: The Next-Generation In-flight Separator for Exotic Nuclei at Relativistic Energies

Abstract

The Super-FRS will be the most powerful in-flight separator for exotic nuclei up to relativistic energies. Rare isotopes of all elements up to uranium can be produced and spatially separated within some hundred nanoseconds, thus very short-lived nuclei can be efficiently studied. The Super-FRS is a large acceptance super conducting fragment separator with three branches feeding different experimental areas including a new storage ring complex. The new rare isotope facility is based on the experience and successful experimental programme with the present FRS. The Low-Energy Branch of the Super-FRS is mainly dedicated to precision experiments with energy-bunched beams stopped in a gas cell. This branch is complementary to ISOL facilities since all elements and short-lived isotopes can be studied. Reaction studies under complete kinematics, as at the present ALADIN-LAND setup, will be performed at the High-Energy Branch. Unique studies will be performed in the Ring Branch consisting mainly of a collector ring CR, the NESR and an electron collider (eA). Though the CR will mainly be used for the efficient collection of the fragment beams from the Super-FRS precision mass and lifetime measurements of short-lived nuclei can also performed in this ring in its isochronous mode. Precision experiments with a brilliant electron-cooled exotic beam including reaction studies with the atoms of an internal target will be done in the NESR. One novelty will be electron scattering from exotic nuclei in the eA collider section.

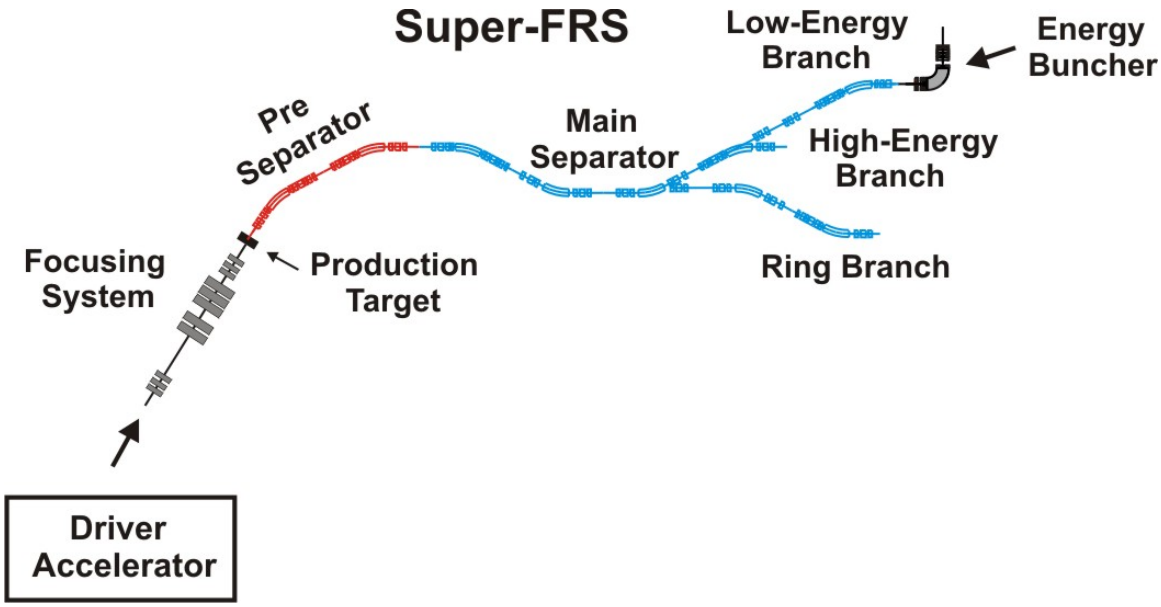


Figure 1: Layout of the proposed super-conducting fragment separator Super-FRS for the production, separation, and investigation of exotic nuclei. Spatially separated rare-isotope beams are delivered to the experimental areas via different branches.

Super-FRS Collaboration

All participating institutes working at the different branches of the Super-FRS have indicated that they will actively contribute in the design, construction and commissioning phases of the Super-FRS and its experimental setups. Only in discussions with these users we will find the optimal parameters such as magnet and focal plane detector configurations. Many technical contributions will come also from the GSI infrastructure and accelerator groups as successfully practiced with the FRS project. The specially listed institutes have indicated to contribute on specific challenging subprojects.

GSI Darmstadt, D-64291 Darmstadt, Germany

Justus-Liebig Universität Gießen, D-35390 Gießen, Germany

Institute of Analytical Instrumentation, RAS, 198103 St. Petersburg, Russia

Michigan State University, East Lansing, MI 48824, USA

Argonne National Laboratory, Argonne, IL 60439, USA

St. Petersburg State Technical University, 195251 St. Petersburg, Russia

Johannes Gutenberg Universität, D-55099 Mainz, Germany

Technische Universität Dresden, D-01062, Germany

Philipps Universität Marburg, D-35032, Germany

Fachhochschule Mainz, D-55099 Mainz, Germany

Babcock Noell Nuclear, D-97080 Würzburg, Germany

Technische Universität Darmstadt, D-64289 Darmstadt, Germany

Forschungszentrum Karlsruhe, D-76344 Eggenstein-Leopoldshafen, Germany

Riken, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

CAE, Saclay, F-91191 Gif-sur Yvette, France

University of Surrey, Guildford, GU2 5XH, UK

Univeridade de Santiago de Compostela, E-15706 Santiago de Compostela, Spain

Technische Universität München, D-85748 Garching, Germany

Comenius University Bratislava, Sk-84248 Bratislava, Slovakia

Spokesperson: Hans Geissel, GSI Darmstadt, Germany

Deputy: Martin Winkler, GSI Darmstadt, Germany

1. The Superconducting Fragment Separator

The GSI projectile fragment separator FRS [1] has demonstrated in many pioneering experiments the large research potential of in-flight separators with exotic nuclei at relativistic energies. Although the FRS has been operated mainly as a versatile separator, many discoveries have been made using the performance of a high-resolution magnetic spectrometer. The present facility has contributed much to the progress in various fields of science and applications but major improvements are still desirable in the future. This leads directly to the new project of the next generation in-flight facility, the Super-FRS [2,3].

The Super-FRS is a large-acceptance superconducting projectile fragment separator with different experimental branches including a combination with a new storage-cooler ring system. This system consists of a Collector Ring (CR) and a New Experimental Storage Ring (NESR) which allow precision mass and lifetime measurements as well as in-ring reaction studies. The NESR can be operated in combination with an electron ring (e-A collider) to measure electron scattering of exotic nuclei. This electron ring can also be used to store antiprotons for antiproton-nucleus collisions

The main goals of the Super-FRS facility are:

- High intensity of the primary beams (1-3×10^{12} ions/s for all elements ($Z \leq 92$)) with energies of up to 2200 MeV/u (A/q=2).
- Large transmission for projectile fragments (100%) and for fission fragments produced by uranium projectiles (30-80%).
- Full transmission of separated fragments to the dedicated experimental areas.
- Large acceptance of fragments by the storage-cooler ring (>80%).

Table 1: Comparison of the ion-optical characteristics of the FRS and the Super-FRS

Facility	Max. Magnetic Rigidity $B\rho_{max}$ / [Tm]	Momentum Acceptance $\Delta p/p$	Angular Acceptance ϕ_y / [mrad]	ϕ_x / [mrad]	Momentum Resolution
FRS	18	±1 %	±7.5	±7.5	1500 (ε=20π mm mrad)
Super-FRS	20	±2.5 %	±40	±20	1500 (ε=40π mm mrad)

The proposed Super-FRS is a powerful in-flight facility, which will provide spatially separated isotopic beams up to elements of the heaviest projectiles. It is superior to the present FRS due to the incorporation of more separation stages and larger magnet apertures through the use of superconducting coils. The Super-FRS will be used as a fragment separator including the possibilities to compress the energy spread and as a versatile high-resolution magnetic spectrometer. It is based on results, experience, methods and techniques, which were pioneered and developed for relativistic heavy ions at the FRS. Moreover, the still needed R&D for the Super-FRS will be performed in experiments with the FRS.

1.1 Production targets

The properties of the production targets are mainly determined by the intensity, energy, time structure and Z of the primary beam. The high intensity and the time structure of the synchrotrons SIS100/300 [3] require new technical developments for the production targets. The different experiments clearly demand two different types of targets depending on the extraction mode. The experiments performed in the low- and high-energy branch require slow extraction from SIS100/300, whereas in combination with the storage rings, only the fast extraction mode provides an efficient injection of secondary beams into the storage rings.

Using slow extraction, the intensity of the primary beam can be distributed over several seconds or in a quasi-continuous mode. Detailed studies have shown that effective cooling and the use of rotating graphite wheel targets are two measures necessary to successfully cope with the power density in the targets. We foresee a liquid cooled target wheel mounted on a tube. The target handling for slow extraction is therefore feasible with current technology; however, further research and development as to the realization is required particular the pressure buildup in the material due to the temperature gradient has to be taken into account.

Experiments with the storage-cooler rings require targets to withstand fast-extracted beams. Two-dimensional hydrodynamical calculations have been performed to understand the target properties under the conditions of fast extraction. An important result of these studies is that the extraction times should be 100 ns or less to avoid density fluctuations during the time that the beam penetrates the target. Only in the range below 100 ns there is practically no hydrodynamic expansion of the target material during irradiation. However, the enormously large power deposition results in a temperature increase of more than 10^4 K which exceeds the melting point of any solid target material. This means also that the target has to be replaced after each high-intensity pulse. Possible solutions could be to use a windowless liquid lithium or sodium target, which is a technology that is presently under investigation.

The same technical effort and challenge represents the extended stopper region for the primary beam in the first dipole stage up to the slit system in front of the first degrader stage. Although in general the beam spot is much enlarged compared to the conditions at the target, the situation is still a great challenge since here the full kinetic energy has to be deposited whereas in the target only about 10-20 % is lost. The beam dump and the corresponding magnet design will still need a large amount of R&D work.

1.2 Pre- and Main-Separator

The Super-FRS has to efficiently separate in-flight rare isotopes produced via projectile fragmentation of all primary beams up to ^{238}U and via fission of ^{238}U beams. The latter reaction is a prolific source of very neutron-rich nuclei of medium mass. However, due to the relatively large amount of kinetic energy released in the fission reaction, the products populate a large phase space and thus determine the need for a much larger acceptance for the Super-FRS compared with the FRS, see table 1. The gain of the Super-FRS in transmission for uranium fission products is more than an order of magnitude compared to the FRS.

Besides the fragment intensities, the selectivity and sensitivity are crucial parameters that strongly influence the success of an experiment with very rare nuclei. A prerequisite for a clean isotopic separation is that the fragments have to be fully ionized to avoid cross contamination from different ionic charge states. Multiple separation stages are necessary to efficiently reduce the background from such contaminants. Based on the experience of successful spatial isotopic separation with the FRS, the Super-FRS also uses the $B\rho$-ΔE-$B\rho$

method, where a two-fold magnetic rigidity analysis is applied in front of and behind a specially shaped energy degrader. The strong enhancement of the primary beam intensity expected with the SIS100/300 synchrotron requires additional measures to achieve the required separation quality. A solution is an additional degrader stage which provides an effective preselection before the fragment beam impinges onto the main degrader. A straight forward consequence is that the Super-FRS consists of a two-stage magnetic system, the pre- and the main-separator are each equipped with a degrader.

The above-mentioned condition for fully stripped fragments requires a high-energy operating domain. On the other hand, the thicknesses of the production target and degraders have to be optimized to prevent substantial losses due to secondary nuclear reactions. The selection of the max. magnetic rigidity of 20 Tm results from these physical criteria and the optimization of the performance and costs of the magnetic elements.

1.3 Ion-optical properties of the Super-FRS

The ion-optical layout of the Super-FRS (High-Energy Branch) and its imaging conditions are presented in figure 2. The envelopes and the dispersion line are plotted for 40 π mm mrad and a $\Delta p/p$ of 2.5 %, respectively. The target spot size is assumed to be ±1 mm and ±2 mm in the x- and y-direction, respectively. The system consists of the pre-separator and the main-separator, each equipped with an energy degrader stage. The pre- and main-separator are both achromatic systems, hence the complete system is also achromatic. This means the image size at the final focal plane is independent of the momentum spread of the fragments at the entrance of the system and thus guarantees the best spatial isotopic separation.

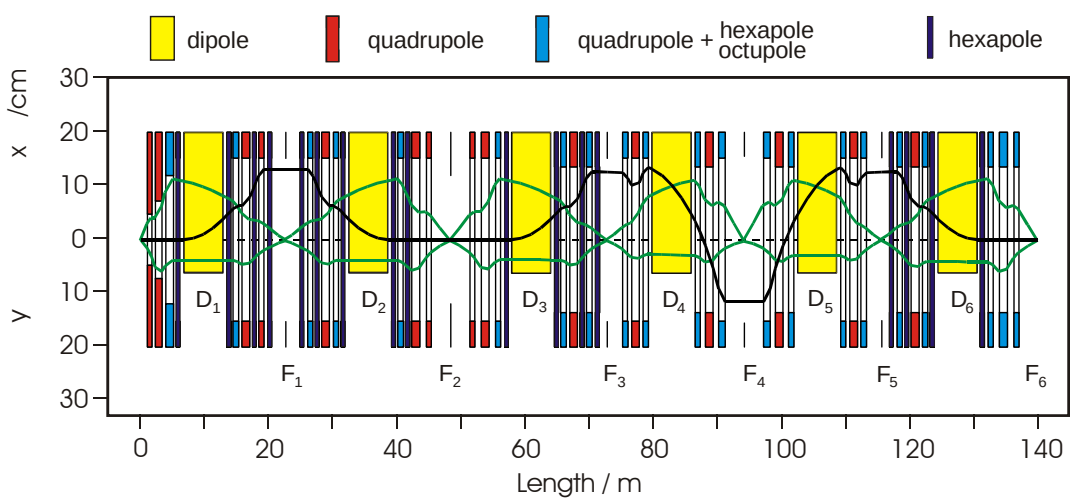


Figure 2: Ion-optical elements, beam envelopes (green lines) and the dispersion line for 2.5 % momentum deviation (black line) are shown in the lattice of the Super-FRS. The envelopes result from an emittance of 40 π mm mrad in x and y direction. The 28°dipole magnets are indicated by D_1 - D_6 and the different focal planes by F_1 - F_6. Quadrupole triplets are placed in front of and behind each of the dipole magnets to achieve the desired ion-optical conditions at the focal planes and to properly illuminate the dipole magnets. Hexapole and octupole magnets are applied to correct image aberrations, especially at the degrader positions and the achromatic focal planes. As an example, the scheme of the High-Energy Branch is plotted.

The detailed magnet design of the Super-FRS is still in progress, although much work has been done to establish basic parameters. The magnet design will optimize manufacturability, easy operation and reliability so that both capital and operational costs are minimized.

The Super-FRS system with the described layout will be a powerful isotope separator and also a versatile high-resolution spectrometer. The synergy of both application results from the fact the separation quality for isotopic beams depends directly on the ion optical resolving power.

1.4 The experimental branches of the Super-FRS

From the experience gained with the FRS and the experimental demands for the next-generation facility, the Super-FRS will have three ion-optical branches delivering the separated exotic nuclei to different experimental areas, see figure 1.

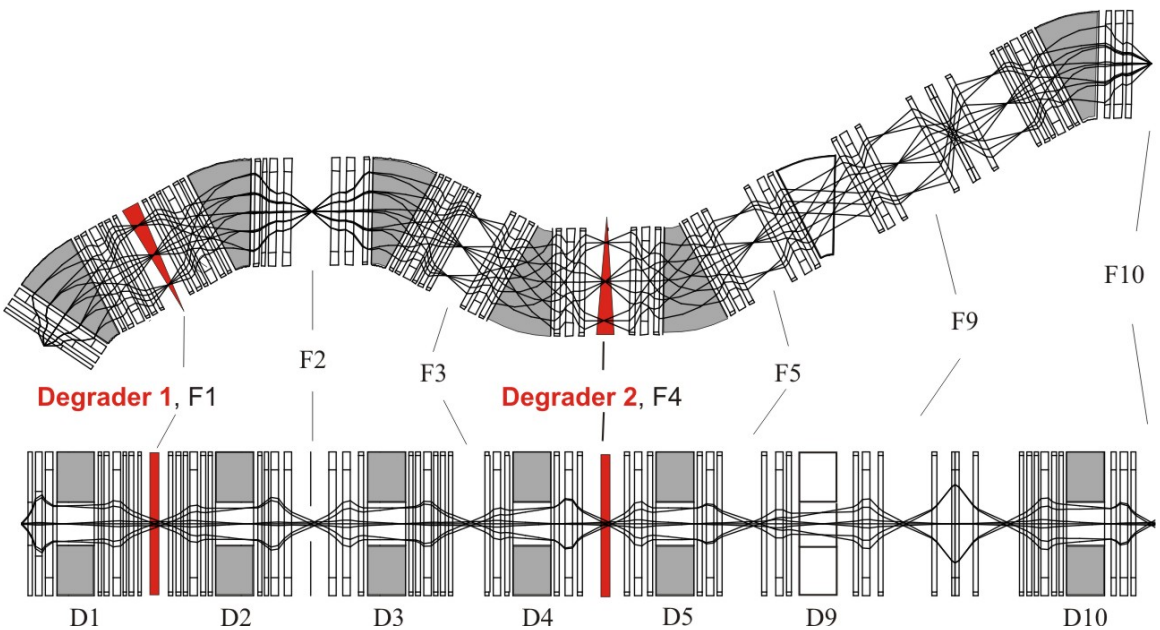


Figure 3: Layout of the Low-Energy Branch of the Super-FRS. The beam passes the inactivated last dipole magnet of the High-Energy Branch. An additional quadrupole triplet guarantees the achromatism of the separator and adjusts the optics for the different geometry. Beam envelopes are shown for an emittance of 40 π mm mrad and a momentum spread of ±2.5% . The initial beam spot size is ±1 mm and ±2 mm in the x- and y-direction, respectively.

The **Low-Energy Branch** (see figure 3), which delivers secondary beams with magnetic rigidities up to 10 Tm, includes a high-resolution dispersive separator stage behind the achromatic pre- and main-separator stages. In combination with a set of profiled energy degraders, including a monoenergetic degrader, this setup has been designed to drastically reduce the energy spread and thus the range straggling of the hot fragments [4], which is an indispensable requirement to stop and cool the exotic beams efficiently in a gas cell and to quickly transfer them to ion or atom traps. This is a novel experimental technique which will

combine the advantages of the in-flight separation method with the ISOL concept and is described in detail in the LoI of the Low-Energy Branch

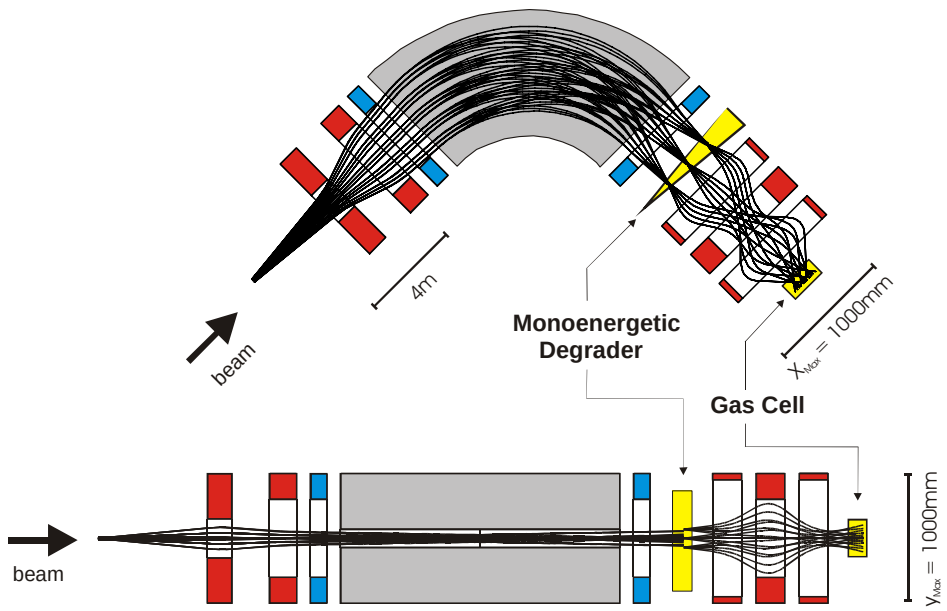


Figure 4: Layout of the Energy Buncher at the end of the Low-Energy Branch of the Super-FRS. The combination of a dispersive dipole stage and a monoenergetic degrader allows to suppress the initial momentum spread considerably, such that the exotic nuclear beam can be stopped in an approximately 1 m long gas cell. Beam envelopes are shown for an emittance of 300 π mm mrad in x- and y-direction. The initial beam spot size is ±15 mm and ±10 mm in the x- and y-direction, respectively. The accepted momentum spread is ±2.5 %.

The **High-Energy Branch** allows experiments with fast secondary beams up to a $B\rho_{max}$ of 20 Tm. It combines the in-flight separator with an efficient reaction setup [5]. The experiments foreseen in the high-energy branch cover a large variety of different reactions, such as elastic scattering, knockout reactions, electromagnetic and nuclear excitations, charge-exchange reactions, fission studies, in-beam γ-ray spectroscopy, or multi fragmentation. The planned setup builds on the experience gained with the present ALADIN-LAND [6,7] and KAOS [8]experiments.

Of special importance is the **Ring Branch,** see figure 5, which combines the Super-FRS with three storage-cooler rings, the Collector Ring (CR), the Recycled Experimental Storage Ring (RESR), and the New Experimental Storage Ring (NESR). Fragment pulses as short as 50 ns are injected into the CR with rigidities of up to 13 Tm [9]. The main task of the CR is to efficiently collect and stochastically precool the hot fragment beams, while the RESR can be used for deceleration of the beams. The NESR is equipped with various experimental facilities, including an eA-collider, as described in detail in the LoI of the Ring Branch.

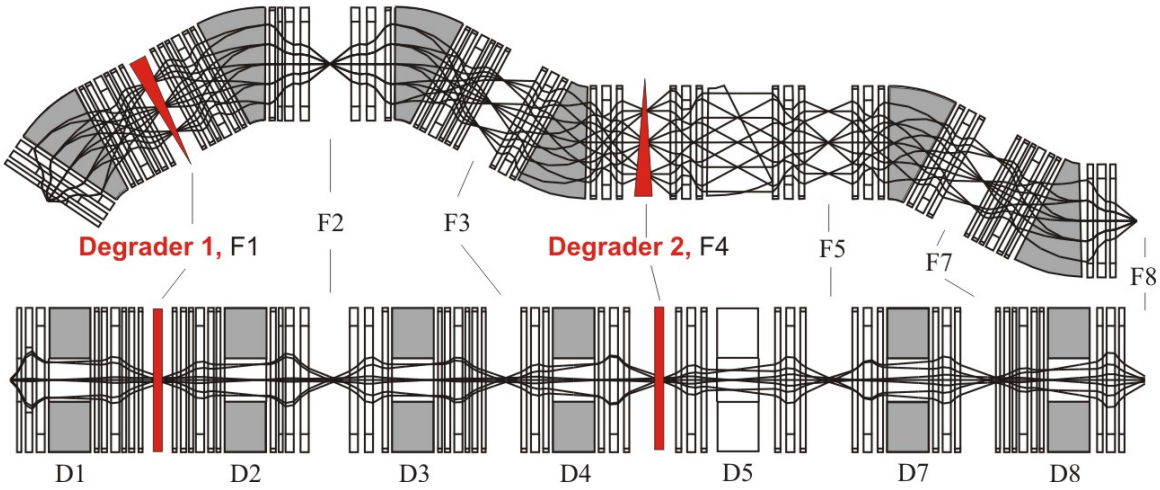


Figure 5: Layout of the Ring Branch of the Super-FRS. After the inactivated third dipole magnet of the main-separator the ion beam passes two additional dipole stages which form the second half of this branch. Beam envelopes are shown for an emittance of 40 π mm mrad and a momentum spread of ±2.5 %. The initial beam spot size is ±1 mm and ±2 mm in the x- and y-direction, respectively.

1.5 Diagnostic and particle identification at the Super-FRS

Experiments with exotic secondary beams at the Super-FRS require a complete particle identification of the projectile and fragment before and after the secondary reaction target. This involves measuring the magnetic rigidity (Bρ), time of flight (ToF), and the charge (Z). The Super-FRS will be equipped with large-area beam tracking detectors for slow as well as for fast extracted beams. Their task will be to measure the trajectories of ions over a large dynamic range of intensities and projectiles. The Super-FRS data acquisition concept foresees distributed subsystems that acquire data (position, time, energy loss, decay radiation etc.) in self-triggered mode synchronized by time stamps; sub-events are sent to the event builder via fast optical links.

Following current trends, we foresee largely digital electronics based on ultra-fast sampling of the direct or preamplifier signals, followed by digital signal processing rather than analog pulse shaping or time pick-off. These concepts have been successfully applied at the present FRS for measuring atomic masses in the ESR via the ToF method, and are indispensable for the readout of future γ-ray tracking detectors like AGATA. Whereas at present such approaches rely largely on expensive commercial modules with small numbers of channels, efforts will concentrate on designing custom-built inexpensive modules that allow digitizing economically the few thousand channels foreseen in the proposed facility.

1.6 Complement and synergy of the Super-FRS with other next-generation projects

New large-scale exotic nuclear beam facilities have gained much interest worldwide due to the great potential for unique research and applications. Both ISOL and in-flight facilities have contributed a lot to nuclear and atomic physics as well as to nuclear astrophysics. In several international working groups it was clearly demonstrated that in future both types of facilities will provide complementary contributions, see NuPECC Report April 2000.

The in-flight separation method based on high-energy projectile fragmentation and fission is universal and provides all nuclei and elements up to the heaviest projectiles. The ISOL facilities generally yield the highest intensities for rare isotopes which have longer half-lives and suitable chemical properties. High energies up to 1500 MeV/u are the basic prerequisite for completely ionized fragments of all elements. The NUSTAR facility at GSI will be superior in separation quality to the new in-flight systems planned in Japan [11] and USA [10] because those will reach only a maximum kinetic energy of 350 and 400 MeV/u for ^{238}U projectiles, respectively. The advantages of a high separation quality due to bare fragments have been clearly demonstrated by the present in-flight facilities. Projectile fragments with Z>80 require relativistic energies of 1000 MeV/u or more to reach this goal. The selection of the accelerator facilities at GSI was driven by the fact that the synchrotron accelerators are most cost-saving to provide projectile energies for heavy ions in the range of 1000 MeV/u and above. The rich research potential of experiments with stored fragments at relativistic energies has also favored the synchrotron scenario. The short bunches of the synchrotrons are ideally tailored to efficiently inject fragment beams in cooler storage rings.

Many research and development tasks for the construction of the Super-FRS facility will be done in collaboration with the members of the other next-generation facilities presently planned or under construction. The advantage of this common effort and synergy was already clearly demonstrated at an international NuPECC workshop at GSI in 1998 where for the first time the feasibility of stopping of relativistic fragments in gases was demonstrated. This new experimental method will be employed at future in-flight facilities including the low-energy branch of the Super-FRS. Other fruitful collaborations are connected to the power-target development and the design of large acceptance super-conducting magnets.

2. Implementation

2.1 Participating Institutes

Table 2: Tasks and responsibilities

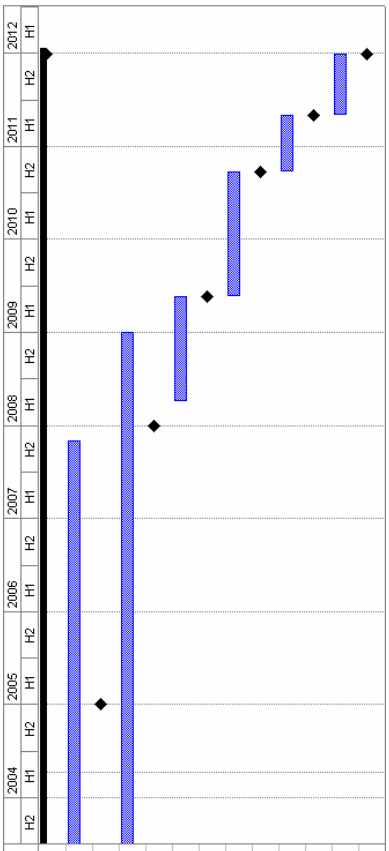
Task	Organisation	Contact
Ion-optical design	GSI, Germany	M. Winkler H. Weick
	Justus-Liebig Universität Giessen, Germany	W. Plass H. Wollnik
	Institute of Analytical Instrumentation, St. Petersburg, Russia	M. Yavor
	National Super Conducting Laboratory, MSU, USA	M. Berz

Production Targets, Degrader	GSI, Germany Forschungszentrum Karlsruhe, Germany Technical University Darmstadt, Germany CAE Saclay, France Argonne National Laboratory, USA Institute of Physical and Chemical Research, RIKEN, Japan	K. Sümmerer B. Lommel B. Kindler R. Stieglitz N. Tahir W. Korten J. Nolen A. Yoshida
Beam Dump	GSI, Germany National Super Conducting Laboratory, MSU, USA Institute of Physical and Chemical Research, RIKEN, Japan Technical University Darmstadt, Germany	K. Sümmerer G. Fehrenbacher T. Radon H. Iwase B. Sherrill T. Kubo N. Tahir
Super conducting Magnets	GSI, Germany National Super Conducting Laboratory, MSU, USA Technical University of St. Petersburg, Russia Babcock Noell Nuclear, Germany Philipps Universität Marburg, Germany	G. Moritz K.-H. Behr M. Winkler A. Zeller A. Kalimov M. Gehring W. Ensinger
Cryogenics	GSI, Germany Technische Universität Dresden Johannes Gutenberg Universität, Mainz	M. Kauschke H. Quack A. Bleile
Detectors, Diagnos-tics, DAQ	GSI, Germany Technische Universität München, Germany Comenius University Bratislava, Slovakia University of Surrey Universidade de Santiago de Compostela, Spain	H. Simon R. Krücken B. Sitar Zs. Podolyak D. Cortina-Gil
Technical infrastructure	GSI, Germany Fachhochschule Mainz, Germany	K.-H. Behr F. Boochs
Radiation shielding	GSI, Germany	G. Fehrenbacher T. Radon

2.2 Time schedule

Table 3: Multi-annual implementation plan for the Super-FRS

Nr.	Multi-annual implementation plan Super-FRS
1	**Super-FRS**
2	Development for the Super-FRS setup at the FRS
3	Technical Report
4	Ion-optical Design Studies, R&D, Prototyping
5	Technical Design Report
6	Setup preseparator
7	Comissioning of preseparator
8	High-Energy Branch
9	Comissioning of High-Energy Branch
10	Low-Energy Branch and Energy Buncher
11	Comissioning of Low-Energy Branch
12	Ring Branch
13	Comissioning of Ring Branch



2.3 Costs

The cost estimates - not including personal - for the Super-FRS given in the Conceptial Design Report are still valid and will be updated when the requirements from the experimental areas are finalized and the research and technical developments for the target and beam dump are finished.

Table 4: Cost estimation for the Super-FRS

	Ring Branch (/k€)	High-Energy Branch (/k€)	Low-Energy Branch (/k€)	Energy Buncher (/k€)
Magnetic elements	21.865	5.510	4.228	4.582
Power supplies	2.199	537	447	356
Vacuum system	1.126	284	218	236
Beam Diagnostics	1.534	387	297	322
Power Target	890	0	0	0
	27.613	6.717	5.189	5.495

References

1. H. Geissel, et al., Nucl. Instr. and Meth. B 70 (1992) 247.
2. ***The Super-FRS project at GSI***
   H. Geissel, H. Weick, M. Winkler, G. Münzenberg et al., Nucl. Instr. and Meth. in Phys. Res. B204 (2003) 71
3. An International Accelerator Facility for Beams of Ions and Antiprotons, Conceptial Design Report, GSI
   (2001). http://www.GSI.de
4. C. Scheidenberger et al., Nucl. Instr. and Meth. in Phys. Res. B204 (2003) 119
5. R3B – Reactions with Relativistic Radioactive Beams
   http://www-land.gsi.de/r3b
6. J. Hubele et al., Z. Phys. A 340 (1991) 263
7. T. Blaich et al., Nucl. Instr. and Meth. in Phys. Res. A314 (1992) 136
8. P. Senger et al., Nucl. Instr. and Meth. in Phys. Res. A327 (1993) 393
9. B. Franzke, Nucl. Instr. and Meth. B24/25 (1987) 18.
10. Rare Isotope Accelerator RIA
    http://www.nscl.msu.edu/future/ria/index.html
    http://www.phy.anl.gov/ria
11. RIKEN Radioactive Isotope Factory T. Katayama et al., Design
    Report November 2000. http://www.rarf.riken.go.jp/ribf/index.html

Theory Network Initiative

Advice on experimental priorities, suggestions, concerted efforts, computing and other requirements

April 13, 2004

Abstract

Parallel to the experimental developments within the NUSTAR community a theory network NUSTAR-Tnet is planned. The intention of this initiative is directed towards two major issues:

(i) In the short term, participation and support already in the early stages of the preparatory and planning phases of the experiments and the physics issues to be addressed.

(ii) Building up a coherent and powerful network from the theoretical groups distributed around Europe and the world with interests in NUSTAR physics. The network will have significant overlap with a broader European Nuclear Theory network, known as ENTnet, which will oversee challenges ahead in all areas of nuclear physics, with special emphasis on specialist workshops and on education and training in nuclear structure and reaction theory.

A. Research Activities of the NUSTAR-Tnet

The first point implies active collaboration among theorists and experimentalists at the early stage of developing and preparing experiments. Major fields of theoretical activity providing also important interaction with experiment will be:

1) Calculations of ground state properties for nuclei far from stability with relevance for mass measurements and astrophysics. This will be a *give and take* between theory and experiment because recent experience shows that standard nuclear models have reached their limits when applied far from stability. Groups working on mean-field and shell model approaches need to make a coherent effort in developing and understanding the systematics of binding energies of nuclei with a exotic proton-to neutron ratios. This applies both to the neutron-rich and the proton-rich side.

2) Measurements and the spectroscopy of weakly bound or even particle unstable nuclei will be the major challenge to nuclear physics in the near future. Nuclear theory is not yet ready for satisfactorily precise calculations in such nuclei systems. Methods have to be developed to describe properly both weakly-bound and unbound nuclei. The structure of the low energy continuum will play a key role in understanding capture and knockout reactions, with especial relevance in stellar environments.

3) The necessity to treat nuclei as open quantum systems is new to theory. Neither mean-field nor shell-model approaches are well equipped for such a task. The problem is apparent from the observation that in exotic nuclei the valence shells are close to the particle threshold with separation energies of the order of 1 MeV or less. In many cases, the valence major shell is split by the particle threshold. Hence, the regular evolution of matrix elements and interactions, on which traditional nuclear structure methods rely, is no longer given and irregularities have to be expected. The mass regions of their appearance must be identified theoretically such that experimental studies of those effects become accessible.

4) To understand the transition from mean-field dynamics to a new type of correlation dynamics among the valence nucleons when going off stability will be another major field of research for the new facility. This is of direct relevance for understanding the appearance of new shell structures or the disappearance of shell structures when approaching the driplines. First indications of this are seen in the results on very small single particle spectroscopic factors from recent breakup and γ-ray coincidence measurements in light nuclei.

5) On the theoretical side, the existing – still rather few –studies of nuclear excitations will be intensified and have to be extended. New methods are to be developed allowing to extend shell model calculations into the continuum. These studies are also intended to identify and develop appropriate tools for spectroscopy above the particle threshold. The identification of low-lying resonances will be highly important for capture processes feeding the rp- and the r-process.

6) Efforts will be made to investigate the widely unexplored intersection of nuclear and atomic and laser physics. Interesting applications can be foreseen for measurements of nuclear shapes and sizes, e.g. by laser spectroscopy or high precision measurements of isotopic shifts along isotopic chains.

7) There is an urgent need to go beyond the level of purely phenomenological structure models working with a set of empirical parameters. Developing approaches which are able to describe nuclei on the level of *ab initio* calculations are an important task for nuclear theory. Such activities are clearly rare in Europe. They are both theoretically and numerically challenging and require a sound background in many-body theory and computational physics. Also, such approaches rely on the availability of powerful computing resources which should be planned for.

8) The connection to modern developments in hadron physics must be established and exploited. For example, systematic investigations of Chiral Perturbation Theory and applications to nuclear matter (both few-body systems and heavier finite nuclei)must become one of the central research activities. The relation of chiral descriptions to other field theoretical approaches must be

clarified, especially on the level of interactions. This might give hints on the origin of three-body forces, typically required for a realistic description of nuclear matter and finite nuclei.

9) Another important interface to hadron physics and the research program envisioned for the PANDA detector is obtained by extending nuclear structure theory into the strangeness sector, i.e. to hypernuclei. This gives access to the SU(3) flavour sector thus enlarging the research field of nuclear structure physics to an important sector. Theory can take advantage of the unprecedented opportunities in production and spectroscopy of single and double hypernuclei at the HESR. This will become the major source on precise information on hyperon-nucleon and hyperon-hyperon interactions which both are not well explored.

10) Research projects using large scale shell model calculations are of high priority for understanding the structure of medium and heavy mass nuclei. This will also help to clarify open questions on nuclear structure issues in astrophysical environments ranging from stellar evolution and explosive nucleosynthesis to the properties of neutrons stars.

11) Weak interactions as seen in nuclear beta-decay are the ideal area to study fundamental symmetries and QCD related aspects like testing the CKM matrix in a nuclear environment. Research projects on these topics must be part of the activities in the Theory Network. An important prerequisite are QRPA and Shell Model nuclear structure calculations and reaction studies of charge exchange excitations.

12) Symmetry considerations, and in particular dynamic symmetries, have been vital for understanding nuclear spectra. New aspects like e.g. pseudo spin symmetry and Mixed Symmetry Shell Model calculations will help to understand nuclear spectra off stability. The evolution of isospin symmetry off stability is not yet explored. The same is true for deformation in strongly asymmetric nuclei.

13) For the design and the analysis of experiments theory must make a coherent effort to maintain and extend the knowledge on reaction studies of rare isotopes with electromagnetic, hadronic and leptonic probes. Reaction theory is clearly a necessity for the understanding of rare beam data on a qualitative level. The concepts of traditional nuclear reaction theory have to be adjusted to the new conditions of reactions with weakly bound nuclei. The role of breakup channels in elastic scattering and non-elastic reactions needs to be investigated. Nuclear reactions at extremely low energies are the ideal tool for studies of stellar and other astrophysical processes in a laboratory. Reaction theory will profit from the extended opportunities of nuclear reactions with inverse kinematics. In parallel with this, reaction models at the higher fragmentation energies applied to elastic scattering, breakup, knockout and electromagnetic dissociation must continue to be developed and tested.

14) Since many-body reaction models do not exist, a synthesis between microscopic structure theory and reaction theory must be made to incorporate and imbed the important few-body and many-body correlations that are taken into account in sophisticated *ab initio* structure models into the reaction matrix elements.

B. Structure of the NUSTAR Theory Network

The organization of a theory network as an indispensable part of the NUSTAR community has been initiated. In this respect we identify the following major tasks:

1) Additional educational efforts to integrate and maintain activities of early stage researchers, including doctoral students and young post-doctoral researchers, both in theory and experiment are required. Such efforts are urgently needed because theory is facing the problem of lacking a wide enough reservoir of long term and permanent positions for young researchers.

2) In the long run, NUSTAR, GSI and ENTnet should be prepared to provide a pool of positions and to support applications among the institutions thus adding to the mobility of the community.

3) Efforts on high level physics training for early stage doctoral and more experienced young post doctoral researchers must be made, e.g. in organizing regular theory schools, either through ENTnet or the existing infrastructure of ECT*.

4) Financial support from national agencies must be organized. NUSTAR as a whole should apply for grants from the well funded FP6 European mobility and the coming up FP7 and ERC programs, e.g. by applying for funding of a Research Training Network.

5) Another important infrastructure issue more on the technical side is to make available powerful computational capacities. Many of the envisioned projects require considerable computational power for numerical simulations on a realistic scale and applications to the analysis of data. This is in particular true for large scale shell model calculations and any *ab initio* nuclear structure calculation. Also, modern reaction studies analyzing a variety of different observables will rely on powerful computing facilities. Grid Computing will be an appropriate technology for involved theoretical calculations and data analysis.

Table 1: Research activities envisioned for the NUSTAR Theory Network

	Research Areas:
1.	Correlation Dynamics in Asymmetric Matter and Exotic Nuclei
2.	Covariant Density Functional Theory for Nuclei and Hypernuclei
3.	Non-relativistic Density Functional Theory
4.	Beyond Mean-Field Theory: Projection and GCM
5.	Links to Hadron Physics in Nuclear Matter and Finite Nuclei
6.	Cluster Structures in Exotic Nuclei
7.	Reaction Dynamics of Exotic Nuclei
8.	Response Functions of Exotic Nuclei and New Modes of Excitation
9.	Charge Densities and Form Factors for Electron Scattering and Laser Spectroscopy
10.	*Ab initio* Nuclear Structure Calculations
11.	Cold and Hot Nuclear Matter and Interactions at Extreme Isospin
12.	Large Scale Shell Model calculations
13.	Shell Model in the Continuum
14.	Nuclear Masses and Superheavy Elements
15.	Nuclear Structure Aspects in Stellar Environments
16.	Symmetries in Exotic Nuclei

Table 2: Contributors

	Name	**Place**	**Indicated Fields of Research**
1.	Aberg, S.	Lund	4,7,14,16
2.	Adamian, G.	Dubna	13
3.	Afanasiev, A.	Notre Dame/Riga	2,3,8,14
4.	Al-Khalili, J.	Surrey	6, 7
5.	Antonenko, N.	Dubna	14
6.	Balantekin, A.B.	Madison	15
7.	Baldo, M.	Catania	1,3
8.	Ban, S.	Stockholm	3, 11, 12, 13, 14
9.	Barbieri, C.	TRIUMF	1, 11
10.	Baur, G.	FZ Jülich	7
11.	Bender, M,	Seattle	3, 14
12.	Bengtsson, R.	Lund	14, 16
13.	Berger, J.F.	Bruyeres-le-Chatel	3
14.	Bertulani, Carlos	MSU	7, 15
15.	Blomqvist, J.	Stockholm	3, 11, 12, 13, 14
16.	Bonaccorso, Angela	Pisa	7
17.	Bonche, P.	Saclay	3
18.	Bortignon, P.F.	Milano	1, 3, 7, 8, 15
19.	Borzov, I. N.	Brussels	15
20.	Bracco, A.	Milano	1, 3, 7, 8, 15
21.	Broglia, R.A.	Milano	3, 8
22.	Bürvenich, T.	Los Alamos/LANL	2, 14
23.	Caurier, E.	Strasbourg	10
24.	Colo’, G.	Milano	1, 3, 7, 8, 15
25.	Cseh, J.	Debrecen	6, 16
26.	Danilin, B.V.	Dubna	6, 7
27.	Dean, David	Oak Ridge	12
28.	Denisov, V.Yu.	Kiev	14
29.	Descouvement, P.	Brussels	6
30.	Dickhoff, Wim	St. Louis	1, 11
31.	DiToro, M.	Catania	11
32.	Dobaczewski, J.	Warsawa	3, 14
33.	Dossing, Th.	Copenhagen	3,8,11,12
34.	Draayer, J.P.	Lousiana	16
35.	Dudek, J.	Strasbourg	3
36.	Egido, J.L.	Madrid	3, 4
37.	Ershov, N.	Dubna	6, 7
38.	Feldmeier, H.	GSI Darmstadt	1, 6,9,10
39.	Frauendorf, S.	Notre Dame/Rossendorf	3,8,11,12
40.	Fuchs, C.	Tübingen	1, 2
41.	Giardina, G.	Messina	14
42.	Ginocchio, J.N.	Los Alamos	2
43.	Gloeckle, W.	Bochum/Bonn	5, 6
44.	Gomez-Camacho, J.	Sevilla	7
45.	Goriely, S.	Brussels	14
46.	Gridnev, K.A.	St, Petersburg	6
47.	Grigorenko, L.	Dubna	6

48.	Grümmer, F.	FZ Jülich	8
49.	Hamamoto, I.	Lund/Copenhagen	1,3,8,16
50.	Haxton, W.	Seattle	15
51.	Heenen, P.H.	Brussels	3, 4, 14
52.	Hencken. K.	Basel	7
53.	Heyde, C.	Gent	16
54.	Hjorth-Jensen, M.	Oslo	1,10,11,12,13
55.	Hussein, M.S.	Sao Paolo	6, 7, 14
56.	Idbetan, R.	Stockholm	3, 11, 12, 13, 14
57.	Isar, A.	Bucharest	13
58.	Ivanova, S.	Dubna	14
59.	Ivanyuk, A.	GSI	14
60.	Johnson, Ron	Surrey	6, 7
61.	Jolos, R.	Dubna	8
62.	Kaiser, N.	TU München	5
63.	Karlgren, D.	Stockholm	3, 11, 12, 13, 14
64.	Kozhuharov, C.	GSI	9
65.	Krewald, S.	FZ Jülich	5, 8
66.	Lalazissis, G.	Thessaloniki	2, 8, 9
67.	Langanke, K.	Aarhus	12, 15
68.	Lenske, H.	Giessen	1, 2, 8,9,11
69.	Li, J.	Lanzhou	14
70.	Liotta, R.J.	Stockholm	13
71.	Lönnroth, T.	Turku	6
72.	Lovas, R.G.	Debrecen	6
73.	Madland, D.	Oak Ridge	2, 14
74.	Martinez-Pinedo, G.	Barcelona	10, 12
75.	Maruhn, J.	Frankfurt	2, 3, 14
76.	Meißner, U.	Bonn, FZ Jülich	5, 6, 8
77.	Meyer, J.	Lyon	3
78.	Muether, H.	Tübingen	1
79.	Nasirov, A.K.	Tashkent	14
80.	Navratil, P.	Livermore	10, 12
81.	Nazarewicz, W.	Oak Ridge	3, 4
82.	Nazmitdinov, R.	Dubna/Palma	3,8,11,12
83.	Nowacki, F.	Strasbourg	10
84.	Ohta, M.	Kobe	14
85.	Oi, Makito	Surrey	4,8,14,16
86.	Okolowicz, Jacek	Cracow	13
87.	Orlandini, G.	Trento	6
88.	Ormand, W.E.	Livermore	10, 12
89.	Pashkevich, V.V.	Dubna	14
90.	Pearson, M.	Toronto	3, 14
91.	Petrovici, Alexandrina	Tübingen/Bucharest	10, 12, 13
92.	Pieper, S.	Argonne	10
93.	Pizzochero, P.	Milano	1, 3, 7, 8, 15
94.	Ploscajczak, M.	Caen/GANIL	12, 13, 15
95.	Polls, A.	Barcelona	1, 11
96.	Ponomarev, V.	TU Darmstadt/Dubna	8, 9
97.	Poves, A.	Madrid	12
98.	Ragnarsson, I.	Lund	14,16
99.	Reinhard, P.G.	Erlangen	2, 3, 14
100	Riisager, K.	Aarhus	6,7,8

101	Ring, P.	TU München	2, 4, 8, 14
102	Roth, R.	TU Darmstad	1, 6,9,10
103	Sandulescu, N.	Bucharest	13
104	Satula,W.	Warsawa	3,8,11,12
105	Schaffner-Bielich, J.	Frankfurt	2, 12, 15
106	Scheid, W.	Giessen	6, 14
107	Schmid, K.W.	Tübingen	10, 12, 13
108	Schramm, S.	Frankfurt	2, 14
109	Schuck, P.	Orsay	6
110	Sobiczewski, A.	Warsawa	3, 14
111	Stevenson, Paul	Surrey	4,8,14
112	Stöcker, H.	Frankfurt	2, 15
113	Stoyanov, Ch.	Sofia	8
114	Suhonen, J.	Jyväskylä	8, 13
115	Thielemann, F.	Basel	15
116	Thompson, I.	Surrey	6, 7
117	Tostevin, Jeff	Surrey	6, 7
118	Trautmann, D.	Basel	7
119	Tsoneva, Nadia	Giessen/Sofia	3, 8
120	Typel, S.	GSI Darmstadt	7, 15
121	Vaagen, J.	Bergen	6, 7, 8,13
122	Van Giai, N.	Orsay	2, 8
123	Van Isacker, P.	Caen/GANIL	16
124	Vertse, T.	Debrecen	6
125	Vigezzi, E.	Milano	1, 3, 7, 8, 15
126	Vitturi, A.	Padua	7, 8
127	Voronov, V.	Dubna	8
128	Vretenar, D.	Zagreb	2, 5, 8, 14
129	Wambach, J.	TU Darmstadt	8, 9
130	Weise, W.	TU München	5
131	Wolter, H.H.	LMU München	7, 11, 15
132	Wyss, R.	Stockholm	3, 11, 12, 13, 14
133	Zagrebaev, V.	Dubna	14
134	Zhao, E.	Beijing	14
135	Zhukov, M.	Göteborg	6, 7
136	Zucker, S.	Strasbourg	12,14

The Low-Energy Branch of the Super-FRS

I. **High-resolution in-flight spectroscopy (HISPEC)**

II. **Decay spectroscopy with stopped beams (DESPEC)**

III. **Precision measurements of very short-lived nuclei using an advanced trapping system for highly-charged ions (MATS)**

IV. **Laser spectroscopy for the study of nuclear properties (LASPEC)**

V. **Neutron capture measurements (NCAP)**

VI. **Antiprotonic exotic nuclides (Exo+pbar)**

Abstract

It is proposed to study properties and phenomena of exotic nuclei employing monoenergetic low-energy beams from the Super-FRS (energies ranging from about 100 MeV/u down to a few MeV/u, stopped beams, and reaccelerated beams of a few 10 keV) and antiprotons. This approach is complementary to the other experimental areas of the Super-FRS and has specific advantages as compared to existing low-energy-beam facilities. Experiments combining RIBs and antiprotons are hitherto unprecedented. With dedicated experimental setups key questions of nuclear-structure physics, fundamental interactions, symmetries, and nuclear astrophysics will be addressed.

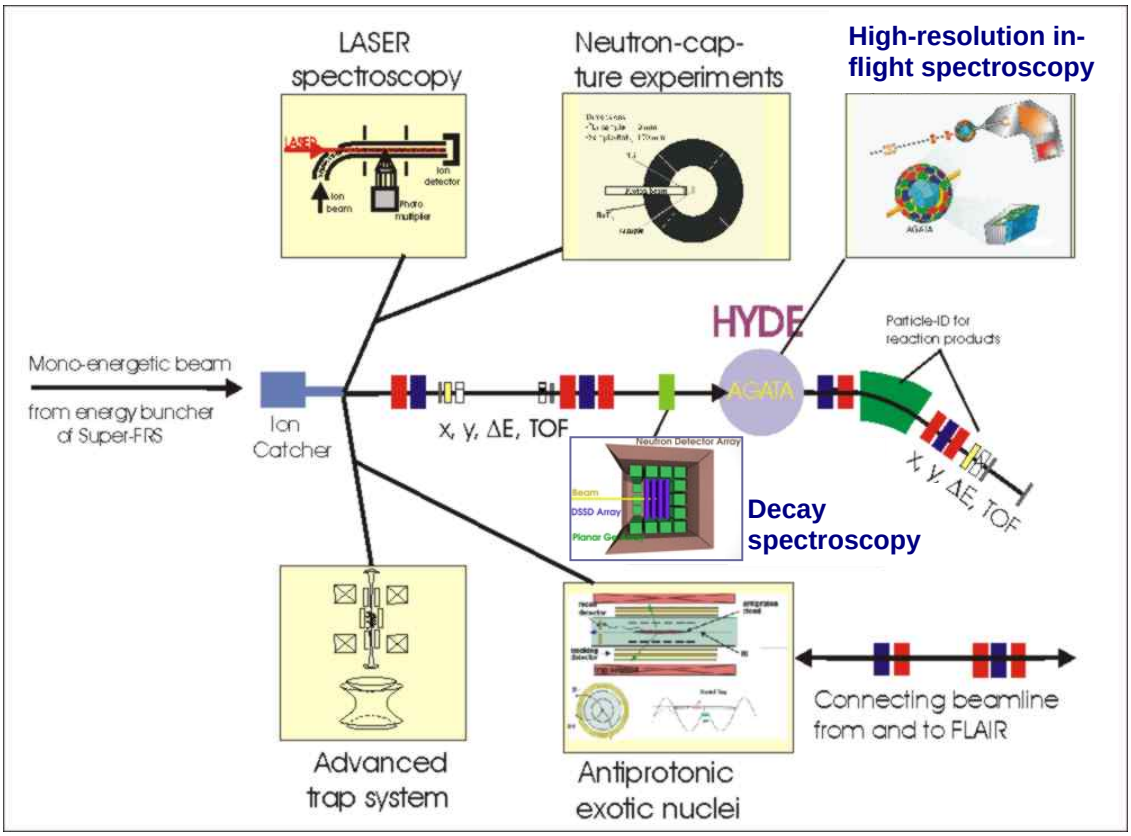


Fig. 1: Schematic layout of the experimental area (35 x 25 m$^{2)}$ of the Low-Energy Branch of the Super-FRS. It comprises set-ups optimized for specific tasks, such as in-beam spectroscopy and reactions, decay spectroscopy with stopped beams, and trapping systems for precision studies, neutron-capture experiments, and the formation of antiprotonic exotic nuclei.

Contents

1. Executive summary

With this Letter of Intent a broad scientific community proposes various setups for experiments with slow, stopped, and reaccelerated exotic nuclei from the Super-FRS and antiprotons at FAIR. The study of the atomic nucleus with extreme proton-to-neutron ratio assures a strong science case and covers a wide range of topics in nuclear structure physics, nuclear astrophysics, test of fundamental symmetries and applications. In these fields, the Low-Energy Branch provides excellent and unique opportunities.

On the world-wide scene, the next-generation radioactive-beam facilities will be based on one of the three principal schemes for exotic-nuclear-beam production: the in-flight method, the Isotope Separation On-Line (ISOL) , and/or a new hybrid concept. The proposed Low-Energy Branch exploits two of them:

1. in-flight separated beams (with particular emphasis on „intermediate“ energy beams characterized by specific kinetic energies of about 100 MeV/u and below) and
2. brilliant beams from a hybrid system, where the exotic species are produced by projectile fragmentation or projectile fission, separated in-flight, stopped in a stopping cell, and extracted with a few 10keV as cooled beams for physics experiments.

In-flight and ISOL facilities are complementary in many respects. As far as secondary beam intensities are concerned, the ISOL method is superior for isotopes of selected elements, i.e. those that are quickly and efficiently released from the target-ion source system. In-flight separation, on the other hand, is independent of chemical properties, and thus yields high secondary beam intensities for **all elements**. The ISOL method is limited by the diffusion time and release and ionization efficiency of the target ion-source system, and is thus in many cases restricted to nuclides with half-lives of seconds or longer. In contrast, the in-flight method gives **access to very short-lived species** with half-lives down to the **sub-microsecond region** and for the hybrid system extraction times of a few ms are in reach. With the proposed layout and the foreseen experiments, **the advantages of both schemes** will be provided. This will be explained in the following.

At the Low-Energy Branch, there are four approaches to access and investigate the exotic nuclei. The energy-focused, low-energy beams from the energy buncher stage can either be

- studied while in flight
- implanted into a detector array
- stopped in and re-extracted from an ion-catcher device (gaseous or superfluid helium)
- merged with antiprotons.

Table 1: Beam energies and accessible half-lives together with the applicable experimental methods.

	E_{kin} (δE)	**Accessible half lives**	**Experimental method / Probe**
Slow to intermediate energy ions	100...3 MeV/u (~1MeV/u)	>100ns	• γ-spectroscopy • nuclear reactions
Implanted ions	0 (thermal)	>100ns	• decay spectroscopy (α,β,γ) • β-delayed neutrons
Stopped and extracted ions	1...100 keV (< 1eV)	>10ms	• charge breeding and ion trapping • neutralization and LASER trapping • LASER spectroscopy • neutron capture • antiprotons

Intermediate energy and slow ions:
In-beam studies at secondary beam energies from a few 10 MeV/u to about 100 MeV/u provide nuclear structure information on single-particle properties, nuclear deformations and intermediate-spin states by means of relativistic Coulomb excitation (Coulex) and secondary fragmentation, respectively. The use of **thick targets** ensures **high luminosities**, so that such reaction studies can be performed at beam intensities as low as 10 to few 100 ions per second depending on the specific reaction.

The energy range around a few MeV/u is the "classical" energy regime for accelerator-based nuclear-structure experiments, which can now be extended to nuclei with the **most extreme isospin** and to the most short-lived nuclei with **half-lives of microseconds** and below. Multiple Coulomb excitation, heavy-ion fusion, and direct reactions are of interest. A beam line connecting the Low-Energy Branch with the FLAIR cave will not only allow to transport antiprotons but will also provide brilliant beams (cooled, slowly extracted from the NESR with energies of 3...10MeV/u corresponding to ~ 1Tm) for high-resolution in-flight spectroscopy on species with half-lives exceeding few seconds.

Implanted ions:
A unique access to decay spectroscopy. **Highest selectivity** and **sensitivity** is due to in-flight separation and **event-by-event identification**, allowing for decay studies at the extreme limits and half-lives. Here it is planned to build a spectroscopy se-tup for **"complete" spectroscopy**, which means a highly efficient detector system for charged-particle detection (α, β, conversion electrons), γ-detection, and neutrons.

Stopped and extracted ions:
The full instrumental spectrum of present and planned ISOL facilities will be used, which allows to address an equally or even more rich scientific programme with exotic nuclei of **all elements** having half-lives exceeding a few milliseconds: precision experiments with trapped radioactive atoms and highly-charged ions probing fundamental symmetries and weak interactions, direct **mass measurements with a precision of 10^{-8} or better for nuclides with half-lives exceeding 10ms**, LASER spectroscopy for the measurement of **charge-radii** and nuclear moments, neutron-capture cross sections, and for the first time experiments with **exotic nuclei from all elements and antiprotons**.

The common requirement of these experiments is the need to slow down the separated ion beams from the Super-FRS quickly and efficiently. A crucial prerequisite is the reduction of their energy spread and range distribution. Both is accomplished simultaneously with a mono energetic degrader system at the dispersive focal plane of the energy-buncher stage behind the Super-FRS. In essence, this is a cooling scheme which acts on the timescale of nanoseconds, and which provides energy-focused secondary beams. For example, the relative momentum spread of a 300 MeV/u fragment beam will be reduced to values as small as $\sigma_p/p = 10^{-3}$ and that of a 6 MeV/u beam to $\sigma_p/p = 0.35$. With this unique feature, so far **not realized elsewhere**, it will be possible to study reactions and to perform γ-spectroscopy at Coulomb-barrier energies with exotic nuclides or isomers having half-lives of **microseconds or below**.

The hybrid system provides many new opportunities. Exotic nuclei of **all elements** having half-lives exceeding a few milliseconds will be available as beams characterized by energies of a few 10keV, **small emittance and high purity**. Not all experimental opportunities can be described here in detail, but the most obvious and new physics opportunities will be sketched and some generic, exemplary set-ups are proposed, which allow already now the realization of key experiments and, in addition to that, have strong potential for new perspectives arising from future developments. It is important to note, that distinct hadronic probes will be employed, as for instance **neutrons** for capture cross-section studies on long-lived species, and for the first time experiments with exotic nuclei from all elements and **antiprotons** will become possible. The latter experiments will particularly benefit from the beamline connecting the FLAIR cave and the Low-Energy Branch.

Table 2: Experimental opportunities and required minimal beam intensities.

Field	**Experimental method**	**Subject**	**Minimal int. (ions/s)**
Nuclear structure and astrophysics	Multiple Coulex, direct reactions, fusion evaporation	B(E2), lifetime, moments, spins, high spin structure, single particle structure, dynamical properties	10^4...10^7
	Intermediate energy Coulex, fragmentation	B(E2), lifetime, moments, spins, shape evolution, shell structure	10^1...10^3
Nuclear structure and astrophysics	α-, β-, γ-, particle-decay spectroscopy	Half-lifes, spins, nuclear moments, GT strength, isomer decay, β-decay branching ratios, β-delayed neutrons	10^{-5}…10^{-2}
Atomic physics methods applied to nuclear structure	Laser spectroscopy	Nuclear charge radii Magnetic dipole and electric quadrupole moments	10^2…10^4
Precision experiments	Ion trapping, charge breeding, and spectroscopy	Nuclear binding energies (mass measurements, Q-values)	1...10^3
Tests of the Standard Model	Atom trapping (MOT)	Half-life measurements β-decay branching ratios β-ν correlations	1...10^3
Nuclear structure and antimatter	RIB+pbar trapping	Charge radii, skin- and halo distributions	10^6 (pbar) 10^3 (RI)

All components will benefit from further developments until operation will start. Rather than leading to a duplication of efforts, it must be noted that these approaches are complementary to the ones pursued at the other branches of the Super-FRS, having specific advantages and unique capabilities. For instance, using implantation detectors in conjunction with particle and γ-ray detectors, half-lives and decay properties of nuclei at the limits of existence can uniquely be reached. Also, precision measurements in ion traps provide the most accurate mass values, which are needed as calibration points for the ILIMA program proposed for the storage ring branch, and, in addition to the science case covered by ILIMA, will allow to probe the Standard Model to the highest levels of accuracy. Innovations will yield a new access to open questions, such as in-trap decay spectroscopy. The experimental studies of strongly interacting systems as outlined here is interrelated with the development of theoretical concepts and will progress in a coordinated effort.

In conclusion, the Low-Energy Branch stands for novel conceptual approaches:

- **cooling scheme acting on a nanosecond time scale** (delivering in-flight separated mono energetic, cooled beams with half-lives down to the **sub-microsecond** regime),
- **brilliant** low-energy exotic nuclear beams of **all elements** (a few 10keV, half-life lower limit of a few ms)
- access to **exotic nuclei + antiprotons**.

Employing top-class instrumentation, the Low-Energy Branch of the Super-FRS opens up a new gate to highest sensitivity and precision experiments with the most exotic nuclei at low energies. It will contribute to maintain forefront research with exotic nuclear beams.

2. Overall implementation

The technical requirements of the individual experimental set-ups are described in the subsequent LoIs, whereas common aspects are discussed in the following.

2.1 Experimental area

The experimental area of the Low-Energy Branch is located behind the energy buncher at the exit of the Super-FRS. An experimental hall of approximately 35 x 25 m^2 floor space is required. This hall should be surrounded by annex buildings for auxiliary equipment, (detector) laboratories, and workshops. Shacks for data-acquisition systems, electronics and components like power supplies, pumps, cryogenic systems etc. can be placed inside the hall next to the installations. A crane should span the whole area. Access to the experimental area for large and/or heavy loads must be provided.

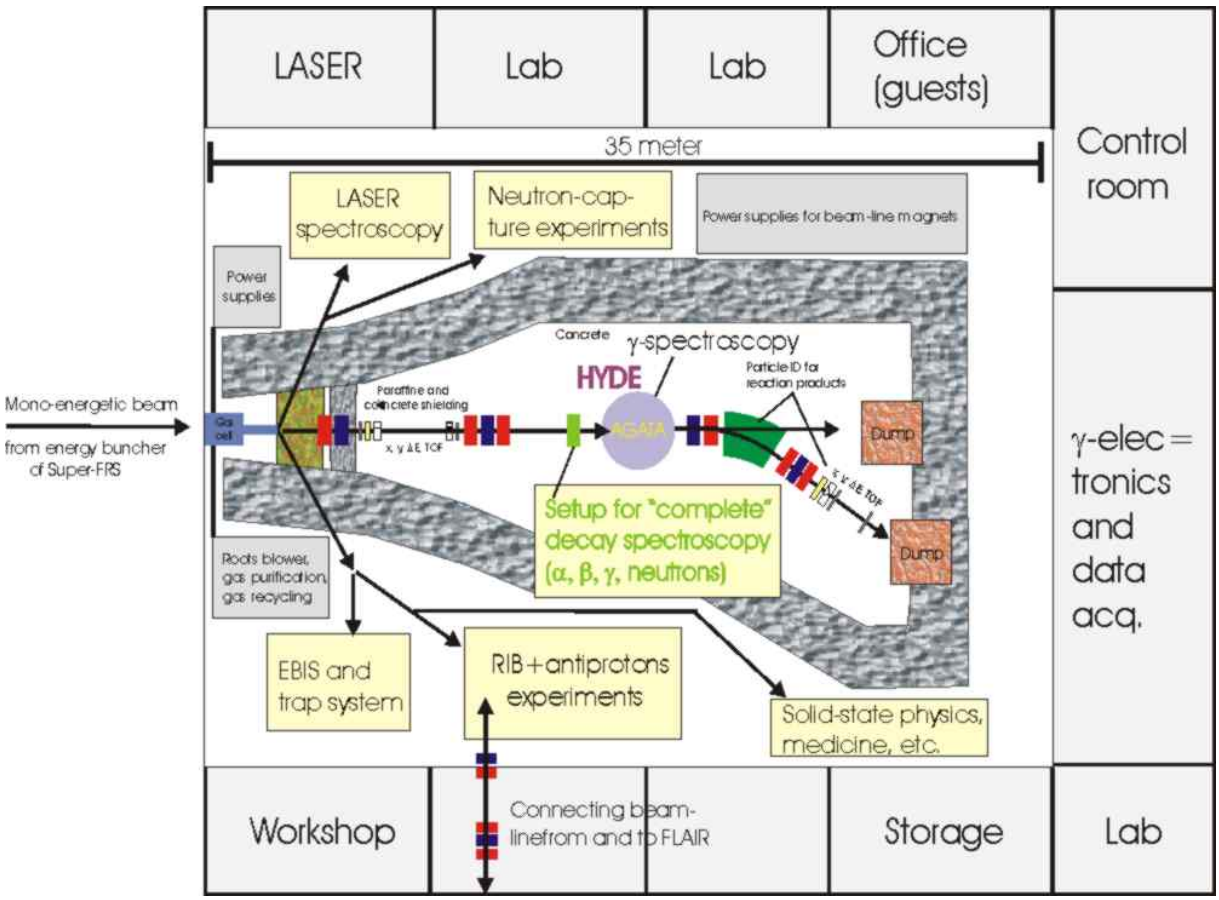


Fig. 2: Schematic view of the layout of the experimental area of the Low-Energy Branch.

The radiation shielding (concrete) should cover the „slow beam line“ and spectrometer (see table) for the energetic beams from the Super-FRS while in flight, the setup for decay spectroscopy with stopped beams, and the stopping cell. Beam dumps are foreseen within the concrete shielding. Special paraffine shielding should be added in front of the decay-spectroscopy setups for in-flight studies and for stopped beams in order to minimize background from the slowing-down process in the mono energetic degrader. Beams extracted from the stopping cell will have kinetic energies of a few 10keV and can be delivered to the experimental setups outside the concrete cave. Possible problems with the activity from intense secondary beams are an issue for further investigation.

Some of the proposed set-ups jointly use the same beam-transport lines and/or beam-preparation components as indicated in table 3:

Table 3: Jointly used parts of the facility.

	Experimental set-up needing components indicated in the left column					
	High-resolution in-flight spectroscopy	Decay spectroscopy with implanted beams	Advanced trap system	Laser spectroscopy setup	Neutron-capture experiments	Antiprotonic exotic nuclei
Slow beam line and spectrometer	X	X	-	-	-	-
Stopping cell, extraction, cooling, beam-distribution system, and electrostatic beam lines	-	-	X	X	X	X
Connecting beam line FLAIR – Low-Energy Branch	X	-	-	-	-	X

The experiments using brilliant few-keV beams are based on the hybrid system and jointly use the devices for beam extraction, cooling, bunching and distribution including electrostatic beam lines to the different experimental setups. Furthermore, some of them use equal components, such as ion traps (used for mass measurements and in-trap spectroscopy, and also for simultaneous trapping of exotic nuclei and antiprotons) or EBITs (used for charge breeding and for X-ray and LASER spectroscopy experiments). It is obvious that synergies will have to be identified in order to make efficient use of available resources and that design, construction, and operation will progress as a joint and coordinated effort. However, at this early stage, where the various collaborations express their intent, a common concept cannot yet be presented. This is an issue of forthcoming efforts.

2.2 Organization

The construction, operation, and organization of the low-energy experimental area will be a collaborative effort of all participants, which will be accomplished within the framework of the NUSTAR community. A formal collaboration for the Low-Energy Branch has not yet been established, but is an issue to be discussed on a workshop planned for mid/end of 2004. The collaboration is open for everybody to participate. It is clear to all present participants that synergies and collaborative efforts will be fostered and the possibilities for networking will be used wherever possible in order to make best use of resources, including human capital. The experimental study and the development of theoretical concepts are strongly interrelated and will progress in a coordinated effort between the experiment and theory groups. The development and implementation of the components, detector systems and setups will be carried out by the collaborations established in this Letter of Intent.

2.3 Data acquisition

The common Super-FRS/NUSTAR data acquisition system will be used wherever possible. This is the case particularly for the experiments using beams in-flight and stopped in the decay spectroscopy setup, where event-by-event identification is necessary. Otherwise, every experiment will provide its own

trigger and data-acquisition system, which is optimized for the specific requirements. Common needs for new developments and improved instrumentation will be jointly identified, coordinated, and realized. Synergies will be identified used as far as possible.

2.4 Implementation strategy and time schedule

Although top-class and leading edge instrumentation is planned, there are no principle obstacles expected, which could endanger the whole project. On the contrary, many key elements like the energy-focusing scheme, stopping cells and extraction, have been tested already and show the expected performance. Other components are under current investigation and will profit from the developments in European activities within the 5th and 6th framework program:

- ION CATCHER (gaseous and super-fluid helium-filled stopping cells)
- NIPNET (spectroscopy experiments in ion and atom traps)
- HITRAP (trapping of highly charged ions)
- Design study (ion optical developments for energy buncher, spectrometer design for particle identification behind HYDE and AGATA, beam-distribution system of stopped and extracted beams)

The construction of the low-energy experimental area and the setup of the various experiments can be performed in parallel to the construction of the Super-FRS and the energy buncher. Thus, experiments can start immediately after completion of the Super-FRS.

Table 4: Components, tasks and the responsible partners.

Component/task	**Institution**
Simulations, ion optics	GSI (Germany) U. Surrey (UK) U. Giessen (Germany)
Stopping cell	Argonne National Lab. (USA) GSI (Germany) JYFL (Finland) KVI (The Netherlands) LMU München (Germany) U. Leuven (Belgium) U. Osaka (Japan) U. Warsaw (Poland)
Beam distribution and transport system	U. Surrey (UK) U. Giessen (Germany) GSI (Germany)
Particle ID and spectrometer for reaction products	GSI (Germany) U.Surrey (UK) U.Giessen (Germany) Partners of the collaborations for • High resolution in-flight spectroscopy, and • Decay spectroscopy of implanted beams
High-resolution in-flight spectroscopy (HISPEC)	Basel, Switzerland Univ. Basel Bergen, Norway, Univ. Bergen Berlin, Germany, HMI Bochum, Germany, Univ. Bochum Bonn, Germany Bruxelles, Belgium, Univ. Brussels Bucharest, Romania, IFIM-HH Buenos Aires, Argentina, CNEA Camerino, Italy, Univ. Camerino Canberra, Australia, ANU Copenhagen, Denmark, NBI Copenhagen Daresbury, UK, CCLRC Daresbury Darmstadt, Germany, GSI

	Darmstadt, Germany, TU Darmstadt Debrecen, Hungary, ATOMKI Gatchina, Russia, PNPI Giessen, Germany, Univ. Giessen Groningen, Netherlands, KVI Huelva, Spain, Univ. Huelva Jülich, Germany, FZJ Jyvaskyla, Finland, JYFL Jyvaskyla Karlsruhe, Germany, FZK Köln, Germany, Univ. Köln Krakow, Poland, IFJ Krakow Leuven, Belgium, KU Leuven Liverpool, UK, Univ. Liverpool Lund, Sweden, Univ. Lund Madrid, Spain, Univ. Autónoma de Madrid Madrid, Spain, CSIC Madrid Manchester, UK, Univ. Manchester München, Germany, TU München New Delhi, India, NSC Osaka, Japan, Univ. Oska Paisley, UK, Univ. Paislay Rehovot, Israel, Weizman Inst. Rehovot Saclay, France, CEA Saclay Santiago de Compostela, Spain, Univ. Santiago Stockholm. Sweden, Univ. Stockholm Srasbourg, France, Univ. Strasbourg Surrey, UK, Univ. of Surrey Uppsala, Sweden, TSL Uppsala Valencia, Spain, Univ. Valencia Warsaw, Poland, Univ. Warsaw and the AGATA collaboration
High-resolution in-flight spectroscopy (HYDE)	CRC Louvain, Belgium CSIC Madrid, Spain CSIC Valencia, Spain GSI Darmstadt, Germany MSU, USA Univ. Autónoma de Madrid Univ. Huelva, Spain Univ. Leuven, Belgium Univ. Lisboa, Spain Univ. Padova, Italy Univ. Sevilla, Spain
Decay-spectroscopy setup (DESPEC)	Bordeaux (France) Darmstadt (Germany) Debrecen (Hungary) Edinburgh (UK) Giessen (Germany) Jyvaskyla (Finland) Leuven (Belgium) Liverpool (UK) Louvain-la-Neuve (Belgium) Madrid (Spain) Mainz (Germany) Munich (Germany) St. Petersburg (Russia) Surrey (UK) Valencia (Spain) Warsaw (Poland)
Advanced trap system (MATS)	CNSM Orsay (France) GSI Darmstadt (Germany)

	JYFL Jyväskylä (Finland) LLNL Livermore (USA) LMU München (Germany) MPI Heidelberg (Germany) U. Brussels (Belgium) U. Erlangen (Germany) U. Giessen (Germany) U. Greifswald (Germany) U. Mainz (Germany) U. Seattle (USA)
LASER spectroscopy setup (LASPEC)	CERN (Switzerland) GSI Darmstadt (Germany) LLNL Livermore (USA) LMU München (Germany) MPI Heidelberg (Germany) Pacific Northwest National Lab. (USA) U. Mainz (Germany) U. Manchester (UK) U. Tübingen (Germany)
Setup for neutron-capture studies (NCAP)	Forschungszentrum Karlsruhe (Germany) ENEA Bologna (Italy) INFN Legnaro (Italy) IFIC Valencia (Spain) Los Alamos National Laboratory (USA) University of Notre Dame (USA) GSI Darmstadt (Germany) Forschungszentrum Rossendorf (Germany) CEA Saclay (France) RCNP Osaka (Japan) Oak Ridge National Laboratory (USA)
Setups for antiprotonic RIBs (Exo+pbar)	GSI (Germany) JYFL Jyväskylä (Finland) RIKEN (Japan) U.Tokyo (Japan) U. Warsaw (Poland)

Table 4 contains the components and tasks identified so far and is understood as an expression of interest of the named institutions. Some participating countries and institutions have expressed their strong interest to provide sizeable contributions to the project. These contributions need to be defined in the near future. Commitments will be defined in Memoranda of Understanding. The process of establishing a collaboration is under discussion. There is common agreement on strong collaboration and cooperation.

2.5 Common costs

Cost for the commonly used beam infrastructure is shown in table 5. The numbers quoted correspond to net capital investment only.

Table 5: Cost estimate for those components which are jointly used by several experimental set-ups.

Slow beamline and spectrometer	1.100 kEuro
Stopping cell, extraction, cooling, beam-distribution system, and electrostatic beamlines	1.770 kEuro
Connecting beamline FLAIR – Low-Energy Branch	1.240 kEuro
SUM	**4.110 kEuro**

2.6 Beam time considerations

The experiments at the Low-Energy Branch can use fast and slowly extracted beams from the SIS100/300. Fast extracion applies for experiments using beams stopped in the ion catcher, whereas slow extraction applies to all experiments „in-flight“ and to decay spectroscopy with stopped („implanted“) beams, where event-by-event identification is necessary. The magnetic rigidity of the beams at the exit of the FRS is limited to 10Tm.

Parallel operation with the antiproton program is possible, for the experiments using RIBs and antiprotons this is even necessary.

2.7 Responsibilities

Spokesperson: C. Scheidenberger (c.scheidenberger@gsi.de)

Conveners (GSI contact):

High-resolution in-flight spectroscopy:	J. Gerl, W. Korten, Z. Podolyák, (J. Gerl)
Decay setup of implanted beams:	P. J. Woods, B. Rubio, K.-L.Kratz, M.Górska, (M. Górska)
Advanced trapping system:	Klaus Blaum, J. R. Crespo López-Urrutia, (F. Herfurth)
LASER spectroscopy setup:	W. Nörtershäuser, J. R. Crespo López-Urrutia, (W. Nörtershäuser)
Neutron-capture measurements:	M. Heil, (K.Sümmerer)
Antiprotonic exotic nuclei:	M. Wada, A. Trzcinska, (W. Quint)

Letter of Intent
for

High-Resolution In-flight Spectroscopy

HISPEC Collaboration

April 7, 2004

Abstract

It is proposed to study the structure of exotic nuclei by high-resolution in-flight spectroscopy, taking advantage of the isotopes produced at the Super-FRS facility at FAIR. Mono-energetic beams in the range 3 MeV/u to 100 MeV/u available at the Low Energy Branch of the Super-FRS will be used for γ spectroscopy employing multiple Coulomb excitation, direct reactions and compound reaction at barrier energies as well as single step Coulomb excitation and fragmentation at inter-mediate beam energies. The set-up will comprise beam particle identification and tracking detectors before an active reaction target surrounded by the 4π Ge γ tracking array AGATA. At intermediate energies beam -like particle tracking and identification by a magnetic spectrometer (e.g. ALADIN) is foreseen. For low energies the HYDE heavy particle array for reaction studies and a complete suite of ancillary detectors including a velocity filter added to the magnet separator is planned.

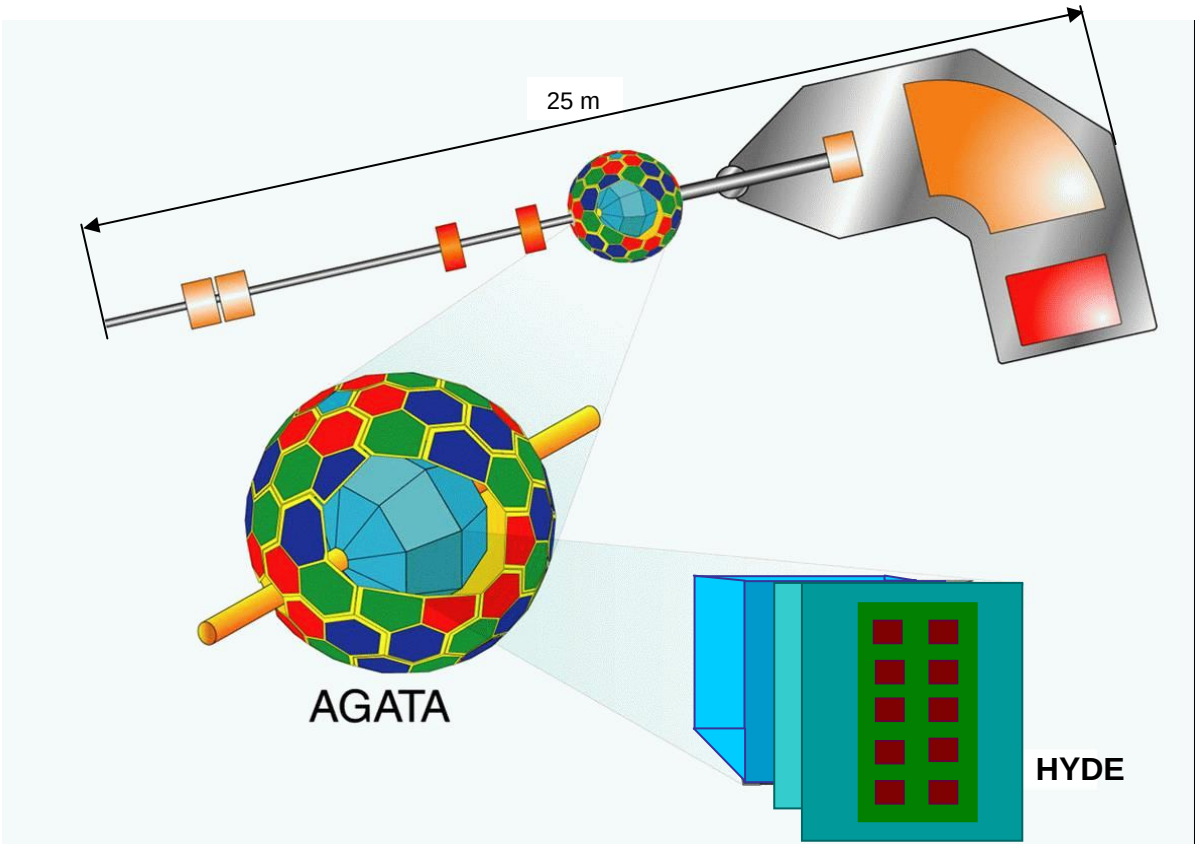


Fig. 1: One of the proposed experimental set-ups, showing the AGATA γ detector array [1], charged particle detectors and a large acceptance spectrometer. Other detectors systems, not shown in this figure, will be used too. The total length of the set-up situated in the Low Energy Cave is about 25 m.

Collaboration

Basel, Switzerland, Univ. Basel, K. Hencken
Bergen, Norway, Univ. Bergen, J. Vaagen
Berlin, Germany, HMI, W. v. Oertzen et al.
Bochum, Germany, Univ. Bochum, W. Gloeckle
Bonn, Germany, K.H. Speidel et al.
Bruxelles, Belgium, Univ. Brussels, I. Borzow
Bucharest, Romania, IFIM-HH, A. Petrovici
Buenos Aires, Argentina, CNEA, A. Kreiner
Camerino, Italy, Univ. Camerino, D. Balabanski
Canberra, Australia, ANU, G. Dracoulis
Copenhagen, Denmark, NBI Copenhagen, G. Sletten
Daresbury, UK, CCLRC Daresbury, J. Simpson et al.
Darmstadt, Germany, GSI, D. Ackermann, F. Becker, P. Bednarczyk, H. Feldmeier, J. Gerl, M. Górska, S. Mandal, N. Saito, T. Saito, Ch. Scheidenberger, M. Tomaseli et al.
Darmstadt, Germany, TU Darmstadt, D. Redondo
Debrecen, Hungary, ATOMKI, Zs. Dombradi, A. Krasznahorkay, D. Sohler, A. Algora
Edinburgh, UK, Univ. Edinburgh, P. Woods
Gatchina, Russia, PNPI, Y. Novikov
Giessen, Germany, Univ. Giessen, H. Lenske, M. Petrick et al.
Groningen, Netherlands, KVI, H. Woertche
Heidelberg, Germany, MPI Heidelberg, H. Scheit
Huelva, Spain, Univ. Huelva, I. Martel, J. E. Garcia-Ramos, F. Perez-Bernal, J. Rodríguez-Quintero
Jülich, Germany, FZJ, G. Baur
Jyvaskyla, Finland, JYFL Jyvaskyla, J. Aysto, R. Julin, M. Leino, P. Greenlees et al.
Köln, Germany, Univ. Köln, J. Jolie, P. Reiter, A. Dewald et al.
Krakow, Poland, IFJ Krakow, A. Maj, J. Styczen et al.
Legnaro, Italy, INFN, A. Stefanini, L. Corradi
Leuven, Belgium, KU Leuven, P. v. Duppen, M. Huyse, G. Neyens
Lisboa, Portugal, Univ. Lisboa, R. Crespo
Liverpool, UK, Univ. Liverpool, P. Nolan et al.
Louvain, Belgium, CRC, C. Angulo
Lund, Sweden, Univ. Lund, D. Rudolph, C. Fahlander et al.
Madrid, Spain, Univ. Autónoma de Madrid, A. Jungclaus
Madrid, Spain, CSIC Madrid, O. Tengblad and M. J. G. Borge
Manchester, UK, Univ. of Manchester, D. Cullen
München, Germany, TU München, R. Krücken et al.
New Delhi, India, NSC, S. Muralithar
Osaka, Japan, Univ. Osaka, Y. Fujita
Padova, Italy, Univ. Padova, G. Motagnoli, A. Vitturi
Paisley, UK, Univ. Paislay, B. Chapman, K. Spohr et al.
Rehovot, Israel, Weizman Inst. Rehovot, M. Haas et al.
Saclay, France, CEA Saclay, W. Korten et al.
Santiago de Compostela, Spain, Univ. Santiago, P. Benlliure
Sevilla, Spain, Univ. Sevilla, J. Gomez-Camacho, J. Espino
Stockholm. Sweden, Univ. Stockholm, B. Cederwall, A. Johnson et al.
Studsvik, Sweden, Univ. of Uppsala, H. Mach
Strasbourg, France, Univ. Strasbourg, J. Dudek
Surrey, UK, Univ. of Surrey, J. Al-Khalili, Zs. Podolyák, P.M. Walker, P.H. Regan et al.
Uppsala, Sweden, TSL Uppsala, J. Nyberg
Valencia, Spain, Univ. Valencia, B. Rubio et al.
Warsaw, Poland, Univ. Warsaw, J. Kownacki et al.

AGATA collaboration, 40 institutions of 10 countries

Convener: J. Gerl (GSI Darmstadt), W. Korten (CEA Saclay), Zs. Podolyák (Univ. Surrey)
Corresponding author: z.podolyak@surrey.ac.uk

Contents

1. Introduction and Overview

The physics case for the High-Resolution In-Flight Spectroscopy proposal is part of the NUSTAR physics programme. It emphasizes on those aspects of nuclear structure investigations with rare isotope beams which can be uniquely addressed with the described high resolution spectroscopy set-up or which complement other parts of the NUSTAR programme in a favourable way.

The low energy branch were the set-up will be located is unique in several aspects:

- several thousands of isotopes of all elements between uranium and hydrogen can be uniquely prepared as beams with energies from about 3 MeV/u to 100 MeV/u and with intensities appropriate for in-flight spectroscopy,
- ions with very short lifetimes (a few 100 ns) can be studied,
- beams composed of several isotopes, mono isotopic beams and beams in high spin isomeric states will be available,
- the beam quality enables high resolution γ spectroscopy, including angular correlations, polarization, g-factor and lifetime measurements,
- for energies around the Coulomb barrier employing the NESR (which provides an energy definition of 10^{-4}) even high resolution particle spectroscopy becomes possible.
- In addition to regular spectroscopic studies, electro-magnetic moments can be measured, at sub barrier energies using tilted foils for polarization and Quadrupole moments (magnitude and sign) [2].

Table 1: Experimental opportunities for in-beam spectroscopy at the low-energy branch

Research field	**Experimental method**	**Physics goals**	**Beam int.** (part./s)
Nuclear structure and astrophysics	Multiple Coulex, direct reactions, fusion evaporation	B(E2), lifetime, moments, high spin structure, single particle structure, dynamical properties	$10^4...10^7$
	Intermediate energy Coulex, fragmentation	B(E2), lifetime, moments, medium spin structure, shape evolution, shell structure	$10^1...10^5$

Beams as low in energy as 3 MeV/u can be produced with the energy buncher and suitable degraders. Depending on the isotope of interest between 10% and 30% of the nuclei disintegrate during the slowing down procedure. By measuring the charge of the final beam species contaminants will be discriminated to a tolerable fraction of < 5%. The energy variation and beam spot spread can be taken into account by measuring TOF and by tracking the individual ions. In this mode the shortest lifetimes can be accessed. As an alternative slowing down and cooling in the NESR is proposed if a beam quality even superior to low energy accelerators is demanded and if the lifetime of the isotope of interest is above several seconds. The particle identification and tracking set-up together with the 4π γ-array AGATA at the secondary target position provides the basis for a comprehensive nuclear spectroscopy programme using multiple Coulomb excitation, direct and compound reactions. With a suite of ancillary detectors, e.g. the HYDE particle array, all classical experimental methods will be covered.

In Coulomb excitation and fragmentation reactions at 50 MeV/u to 100 MeV/u thick (≤0.5 g/cm^2) targets provide sufficient luminosity to study nuclei even further from stability with beam intensities as low as 10/s. This “intermediate-energy” region will be the main area for in-beam γ spectroscopy at the low energy branch. Higher beam energies are not advantageous in this case due to the strongly increasing

background radiation in particular for very heavy nuclei. Spectroscopy after knock-out and fragmentation of lighter nuclei will be performed at higher energies with the R3B set-up and a forward wall of AGATA detectors at the high energy branch (see there). In contrast to the R3B domain, energies below 100 MeV/u, which are mandatory for sensitive high resolution in-beam studies, require a dedicated set-up e.g. with high rate, in-vacuum tracking detectors and special precautions to minimize background. In addition to the set-up described above, which fits the energy range from 3 MeV/u to 100 MeV/u, identification and tracking of the projectile-like nuclei is necessary. For that purpose an available conventional magnetic spectrometer, e.g. ALADIN, is planned to be used to avoid extra cost. As alternative a $\Delta E/E$ calorimeter is foreseen to circumvent efficiency and selectivity losses of a magnet system imposed by wide charge state distributions.

1.1 In-beam spectroscopy with decelerated beams around the Coulomb barrier

A wealth of nuclear structure information was derived over decades from heavy-ion induced reactions in conjunction with high-resolution γ-ray spectroscopy. Inelastic nuclear scattering, multiple Coulomb excitation, direct reactions and fusion-evaporation at energies around or slightly above the Coulomb barrier are standard tools. It is intriguing to instrumentalize the collected experience in nuclear structure investigations with beams of exotic nuclei. An ISOL scheme for the production of unstable nuclei, equipped with a post-acceleration stage seems most appropriate for that purpose. Depending on chemical properties, however, some elements are difficult to extract from the production target; the time scales for extraction and re-acceleration, in addition, do not allow isotopes with half lives below a few 100 ms to be treated. Moreover, certain beams from very heavy and less abundant isotopes produced in an ISOL facility may be of poor quality due to isobaric and charge state contaminants. Finally each nuclear species requires extensive beam development limiting the number of different isotopes available at any time. For these reasons, the use of secondary low-energy fragment beams uniquely available at the NUSTAR facility is an appropriate complement to ISOL based facilities.

The energy-buncher stage of the SUPER-FRS can decelerate secondary fragment beams to any energy with negligible time delay (< 100 ns), and the beam can be directed onto a target without severe loss in intensity. Although the beam quality in terms of spread in kinetic energy and emittance is rather limited, see details in section 1.1.3.4 and 1.2.4 of the CDR, it imposes no principal limitations. An alternative is deceleration and cooling in the NESR, which provides low energy secondary beams with an excellent energy definition of 10^{-4} and beam spot sizes in the order of <1 mm. Depending on the chosen energy the maximal beam intensity (limited by space charge effects) is 10^6 to 10^7 /s. Half life limitations are in the order of a few seconds. There is the option to build a transfer line from the NESR into the low energy cave, also required for other proposals, or to use an identical spectroscopy set-up in the FLAIR cave.

In contrast to experiments at high energies, only thin targets can be used, of the order of mg/cm^2. Integrated cross sections for multiple Coulomb excitation or fusion-evaporation reactions are of the order of barns. For a cross section of 1 barn and assuming a 4π solid angle coverage for γ-rays and a photo-peak efficiency of >25%, as will be provided by AGATA, one arrives at an observed γ-ray rate of the order 10^{-6} per incident exotic nucleus. Therefore γ. spectroscopy becomes feasible for exotic nuclear beams which can be delivered at intensities of the order of $\sim 10^4$ ions/s and above. Though very exotic nuclear species are excluded from such measurements, the presently known part of the chart of nuclides is covered, for the heavy nuclei with $Z > 50$ even regions beyond can be reached, as seen from Figure 1.17 CDR. Especially on the neutron-rich side spectroscopic information is very scarce aside from ground-state and decay properties.

1.2 In-beam spectroscopy at intermediate energies

Detailed spectroscopic information can be deduced by γ-ray spectroscopy in reactions of secondary beams at intermediate energies of several tens to ~100 MeV/u. Thick targets, of the order of several 100 mg/cm^2, can be used and relevant cross sections are of the order of 0.1 barn. Thus, experiments are

feasible with very modest beam intensities. This was demonstrated in measurements performed at the in-flight facilities GANIL, MSU, RIKEN, and GSI. Such experiments are best performed with energy focused beams at the in-flight terminal of the low energy cave of the SUPER-FRS with the γ-detection system arranged in 4π geometry around the target.

Nuclear collectivity: Projectile Coulomb excitation in heavy ion collisions at beam energies of 40 MeV/u to 100 MeV/u can deliver accurate B(E2) values [3] for states excited in a 0ne-step process.. Measurements of this type allow mapping the evolution of nuclei over the full range of structural dynamics from single-particle to deformation degrees of freedom. Islands of octupole deformations or of other multipolarity can be accessed by the same method. At the proposed facility, the region of nuclei with large neutron excess between the N = 50 and N = 126 shells, will be accessible for the first time. Experimental experience shows that one has to cope with a large bremsstrahlung background in such measurements, the discrimination of which requires a Ge detector array of high granularity like AGATA.

High-spin states: The population of high-spin states in fragmentation reactions is a very novel concept that just starts to be understood and exploited [4]. The process of multi-nucleon knockout in a fragmentation reaction leaves the residual nucleus in a highly excited state with considerable angular momentum. This opens up the spin degree of freedom for structure investigations. Short-lived isomeric high-spin states should be populated likewise, the γ-decay of which could be observed in in-beam experiments in coincidence (tagged) with the decaying fragment.

Nuclear moments: Another unique feature of intermediate-energy reactions concerns the atomic charge state of the fragments. Choosing the appropriate kinetic energy, hydrogen-like and few-electron ions will emerge from the reaction target. In heavy ions extraordinary strong hyperfine fields will thus arise. These can be utilized for the measurement of nuclear moments of short-lived excited states, which enables to determine specific nucleonic (proton/neutron) components of the nuclear wave functions as well as nuclear shapes. The technique used for lifetimes in the range of 10^{-12} s is projectile Coulomb excitation in combination with strong transient magnetic hyperfine fields and electric field gradients[5,6]. Precessions of the nuclear moments are observed in measurements of particle-γ-angular correlations. For the detection of quadrupole precessions, sufficient polarization of the nuclear state is provided by the Coulomb excitation process.

1.3 Physics example

The physics case for high resolution spectroscopy was already addressed in the CDR. Here, only one specific example will be briefly mentioned. Neutron-rich Zr isotopes are very suitable to study the development of deformation, spin-orbit splitting and the disappearance of shell gaps. Semi-magic ^{90}Zr with a closed neutron shell at N=50 and a proton sub-shell closure at Z=40 exhibits no collective behaviour besides octupole vibrations. At N~60 the Zr isotopes become deformed and for ^{104}Zr, the heaviest isotope known, the situation has evolved to one of the most deformed nuclei known at all. This drastic evolution is not very well understood and detailed information about rotational structure and coexistence with less deformed shapes is needed. Theoretically, another dramatic evolution towards spherical nuclei around N=70 might be expected if the (spherical) neutron shell gap changes in a similar way as observed in light nuclei. From ^{104}Zr onwards, lifetimes become much shorter then one second thus severely impairing the possibility to use ISOL beams. The beam intensities available from the Super-FRS allow for multiple Coulomb excitation at barrier energies up to about ^{110}Zr providing energies and B(E2) values. The limit for single step Coulomb excitation at 100 MeV/u is around ^{114}Zr revealing at least the deformation of the first excited state. This would answer the question if a new shell closure occurs already in this mass region. Otherwise for even heavier isotopes towards ^{122}Zr decay properties and possible isomeric decays can be studied with the decay set-up (see decay LoI). Besides key structural information these very neutron rich nuclei may establish r-process waiting points and are thus important for nuclear astrophysics as well.

2. Detector Subsystems

2.1. General comments on the set-up

The experimental set-up for intermediate energy beams has to provide isotope identification and tracking detectors for the incoming beam particles, γ-ray, and possibly electron detector arrays around a secondary reaction target as well as identification and tracking detectors for the outgoing beam. For experiments with beams slowed down further in the Low Energy Branch, the set-up is identical concerning the incoming beams. Although the energy buncher strongly improves the energy definition of the slowed down beams, the final beam quality in terms of emittance and momentum spread is still limited. Therefore, for reactions around the Coulomb barrier the standard suite of light and heavy residue detectors need to be adopted to a wide beam spot and a considerable energy range of incoming beam particles. High quality low energy beams from the NESR are isotopically pure with a well defined beam spot and thus need no identification or tracking.

The community would benefit from a beam line from the FLAIR cave to the LEB cave. By sending the beams of highest quality provided by the NESR to the LEB cave we avoid to install another beam line with magnets and monitoring instrumentation. Moreover, the movement between the caves of the delicate detectors systems is avoided. Currently both options are investigated in detail.

2.2 Beam detection system

The beam identification and tracking detectors have to provide event by event mass, charge, position and direction information. Following the well established scheme used e.g. for the RISING project at GSI [4] Bρ-TOF for mass determination could be used by employing ultra fast scintillators for time and a wire chamber for position determination. The aimed for time resolution is <30 ps and the position resolution is <1 mm. At beam energies around the Coulomb barrier the individual ion energy can thus easily be determined from TOF to < 1%. Charge and a second position determination can be achieved either by segmented, position sensitive Si strip detectors or similar diamond detectors. To avoid excessive energy and angular spread of the incoming particles all detectors need to be very thin and the whole set-up needs to run in vacuum. A set of active targets for beam and secondary reaction monitoring are planned. At intermediate energies diamond strips and segmented scintillators are suitable, whereas for barrier energies active gas targets (segmented proportional counter) are to be developed. Ideally the active target may replace the upstream position and ΔE detectors. Particle rates up to 10^7/s have to be processed, which requires new concepts for the layout of the detectors. Moreover, the layout needs to be optimized for minimal background radiation reaching the γ detector array from upstream the secondary target.

2.3 Gamma-ray detectors

For γ ray detection the AGATA tracking array is proposed, a high efficiency, high resolution Ge detector array. It is specially suited to study gamma rays emitted by moving sources and/or high multiplicity. The most important features are the photopeak efficiency of 25% to 50% at 1 MeV γenergy depending on the γ multiplicity, an angular resolution of <1° ensuring an energy resolution after Doppler correction of ≈0.4% at 100 MeV/u and an event rate acceptance of 0.3 to 3 MHz again depending on the multiplicity. AGATA will be build by a European collaboration of 40 institutions from 10 countries being part of the NUSTAR collaboration. A demonstrator array with 15 Ge crystals is currently being developed an will become available for tests and later use in experiments in 2007. Placed in forward direction this sub-array already provides about 5% efficiency at 100 MeV/u. Since at that energy the Lorentz boost to forward angles is not yet dominating, implementation of the full array is required to take full advantage of the capability of AGATA. Therefore it is proposed to place the AGATA array for a period of time at the low energy branch of the Super FRS. The AGATA Technical Proposal [1] contains all the relevant information about the tracking principle, configuration, data acquisition, resources etc.

2.4 Spectrometer and tracking of outgoing particles

A large acceptance magnetic spectrometer is needed behind the secondary target to determine the mass of the outgoing particle for intermediate energy Coulomb excitation and fragmentation reactions. Since the ion energy is limited to 100 MeV/u existing conventional spectrometers like ALADIN can be used for that purpose avoiding extra cost. As alternative a stacked ΔE/E calorimeter is planned to be developed to circumvent efficiency and selectivity losses of any magnet system imposed by wide charge state distributions. In addition the charge, position and TOF of the outgoing heavy ion needs to be determined. For that purpose thin Si strip detectors or diamond detectors as well as plastic detectors may be chosen as described in section 2.2.

Recoil Decay Tagging (RDT) [7] has proven to be one of the most powerful tools to study the nuclear structure of exotic species. A typical setup consists of a γ-ray detection part and an ion-optical separation and particle identification part [8]. Various set-ups are presently in use in many laboratories, like e.g. the FMA+GAMMASPHERE at ANL, PRISMA+CLARA at LNL, VAMOS+EXOGAM at GANIL, RITU+JUROSPHERE at Jyväskylä. An ion-optical unit, like ALADIN, built behind AGATA, will provide the necessary separation of the wanted species from the background and/or the particle identification. This will be realized with various options. In the first mode it will be used as a magnetic tracking device where the products of transfer reactions will be traced through the set-up. This provides together with energy and energy loss measurement mass and charge of the traced particle(VAMOS, PRISMA). The second mode will allow for the study of fusion or fusion-like products. This separator feature will be realized by adding an electro-static component or a velocity filter (LISE, GANIL), or as a gas-filled separator (RITU). This mode will also allow for γ spectroscopy triggered by decay occurring after the separator via evaporation residue-decay-γ coincidence measurements (RITU+GREAT; SHIP, GSI). The focal plane detection system is similar to the one proposed for decay spectroscopy in the Low Energy Branch and will be developed and used together.

2.5 The HYDE-BALL detector array

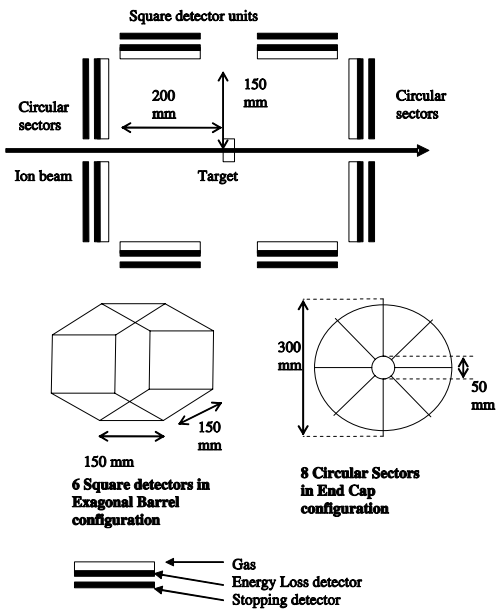


Fig. 2: The HYDE particle detector

The proposed experimental set-up will make use of a specific hybrid detector array (gas + silicon detectors) to be developed in nearest future, named the HYbrid DEtector-BALL array. The proposed

design will fit the experimental conditions that will be imposed by the low energy beam properties in the LEB of the Super-FRS.

To meet the needs imposed by the physics involved, HYDE BALL detector array will incorporate both gas detectors and very compact and highly segmented silicon strip detectors, based on the Double-Sided Silicon Strip Detector (DSSSD) technology. These devices have successfully been used by nuclear physics groups in last few years. It is assumed that the beam diameter is around 2-3 cm, and the beam energy, for energies below 5 MeV/u, can be determined to about 1% of the energy of the beam.

The HYDE-BALL array can be composed of several detector units, arranged over a barrel configuration of hexagonal cross section and 300mm diameter around the reaction target. Two circular end caps of 300 mm outer diameter and 50mm inner diameter will cover backward and forward scattering angles. A possible configuration might comprise 12 square detector units of 150 mm x 150 mm to be mounted on the barrel walls, togther with 8 circular sectors on each end cap (see fig. 2).

Each detector unit might be composed of a Gas Detector, able to detect low energy reaction fragments, and two silicon detector units, one DSSSD of 40 um thickness (Energy Loss Detector) and another silicon back counter of 2mm thickness (Stopping Detector). Each silicon DSSSD device is a highly segmented device, composed of 16 strips of 5 mm width at the front side (X direction), and another 16 strips at the back side (Y direction) . This results in a total of 16x16 discrete detector elements, providing energy and position information for every scattered ion and from each detector unit.

In this way it is possible to extract information on the angular distribution of particles, with an angular range between 10º to 70º (forward), 110º to 170º (backward) and angular resolution of $\Delta\theta < 2.0º$. For low energy scattering events, the combination of the Gas Detector and the Energy Loss detector will provide particle position, charge and mass identification. Higher energy events should be identified using the same technique in combination with the Stop Detector. DSSSD silicon detectors of different widths and shapes fitting required specifications are currently produced by several companies (Micron Ltd-UK, Camberra, etc) and used in several experiments at RIB's facilities elsewhere.

2.6 Ancillary detectors

Ancillary detectors in combination with powerful 4π γ spectrometers tremendously increase the selectivity and sensitivity to successfully investigate subtle nuclear structure effects at low beam energies. Highly specialized and dedicated detector types are available or are being planned for HISPEC by the collaboration. Only some examples can be briefly mentioned here, while a comprehensive description is subject of the technical proposal.

Electron detectors: Orange spectrometers will be used for conversion electron detection. This will allow to determine the character of the transitions etc. Orange spectrometers require very small beam spots, therefore they will be used with low energy beams from the NESR only.

A neutron detector array will be beneficial for most of the proposed experiments. Studies need to be performed to select the most appropriate type whether it is liquid or solid inorganic scintillators. It is envisaged to build a versatile set of neutron detectors which can be used both for in-beam spectroscopy and for decay spectroscopy (see the DESPEC LoI)

A plunger will be used in order to measure lifetimes above >1ps. Based on the existing Cologne plunger, a new one with much larger target-stopper foils, required due to the large beam spot, will be developed.

3. Trigger and Data-Acquisition System

The standard NUSTAR data acquisition system will be used for the tracking and beam identification detectors. AGATA will have an independent acquisition system developed by the AGATA collaboration [1]. The various ancillary detectors usually run with dedicated data acquisition systems. If appropriate the systems will use common master triggers, otherwise total data read-out is foreseen. A time stamp technique will be used to merge the data of the different systems.

4. Physics Performance

A simulation software will be developed on the basis of which feasibility demonstrations for the specific reaction studies of interest can be provided in a conceptual design report. In parallel, prototype detectors will be built and tested, the electronic read-out techniques be developed, the time line being given in table 4. The RISING project is at this moment operational at GSI. With RISING the basic concept of high resolution in-flight spectroscopy at around 100 MeV/u is already realized. Experience is gained and will directly feed into the HISPEC initiative. The slowing down to beam energies around the Coulomb barrier by degraders is part of the project to be developed within the coming two years. On the other hand detectors proposed in this LoI are intended to be used at the current RISING set-up to gain experience and to perform improved experiments at the upgraded FRS. In this sense high resolution spectroscopy towards the set-up proposed in this LoI is seen as an evolutionary development.

5. Implementation

5.1 Experimental area

The required total length of the in-flight set-up located in the Low Energy Cave is 25 m. Besides ion optical considerations the length is determined by the minimal flight path for TOF measurements, the space for the magnetic spectrometer and for AGATA. The width in the upper half of the experimental area needs to be 8 m to accommodate AGATA and the spectrometer. Access to all parts of the set-up is essential to exchange, maintain and reconfigure detectors. Standard electrical power, cooling water and liquid nitrogen infrastructure is required. Provision for air conditioning of electronics and data acquisition is essential. About 200 m^2 of laboratory space for detector maintenance and development needs to be considered as well as a control room for experiments.

For experiments employing brilliant low energy beams from NESR either a connecting beam line from the NESR to the Low Energy Cave is required (schematically depicted on the NUSTAR LoI cover figure), or the set-up without beam tracking and TOF ($\approx 8 \times 8$ m^2) is placed in the FLAIR cave.

5.2 Radiation environment

The radiation environment will be similar to the other branches of the Super-FRS. In most of the cases beam intensities are rather small and the beam will be either stopped in the set-up or in a beam dump. Proper shielding of the γ detectors against radiation and particles, in particular neutrons from up-stream is of very important.

5.3 Cost estimates

Estimates include only instrumentation with electronics and dedicated data acquisition. Buildings, beam lines and general infrastructure are not taken into account. For the magnetic spectrometer it is assumed that an existing dipole magnet, e.g. ALADIN, can be supplied. Therefore only costs for the intended low energy supplement are considered.

AGATA, depending on the adopted configuration will cost 34-50M EUR of which about 5M EUR are already available for the demonstrator. Since AGATA will not stay permanently at FAIR its cost is not included in table 2.

Table 2: Cost estimate for net investment without personnel and excluding AGATA.

Item	Cost estimate (M EUR)
Beam tracking and identification detectors: - Timing scintillators - position detectors - position sensitive ΔE det. - ΔE/E calorimeter - magnetic spectrometer (supplement) - active target - reaction chambers and associated vacuum system	 0.1 0.1 0.3 0.3 2.0 0.3 0.3
HYDE charged particle array	1.1
Ancillary detectors: - neutron array - light charged particle array - plunger	 0.5 0.5 0.1
Total	**5.7**

5.4 Organisation and responsibilities

All of the research teams have experience with regard to scientific or technological aspects addressed in this HISPEC LoI and will participate according to their expertise and physics interests. Participating groups are developing and running the RISING project at GSI and are involved in the EXOGAM project at SPIRAL (Ganil) and the MINIBALL project at REX-ISOLDE (Cern). The AGATA collaboration as a whole takes part in the proposal to ensure proper implementation of the γ-detection array. Collaborative efforts to cover specific detector systems like already established with HYDE (11 groups) are encouraged.

A Management Board (MB) will be formed out of representatives of the participating groups taking over major duties in developing the detector system. At its next meeting, the MB will name the spokesperson and deputy of the HISPEC collaboration. The main duties of the MB are to monitor the progress of the project and the quality of the developments, to ensure the reporting procedure according to the demands of FAIR as well as publication of results, and to guarantee optimal communication between the participants and thus economical usage of the provided funding. For monitoring purpose, the MB will request internal reports from the participants at regular intervals.

To guarantee that various components of the project are properly dealt with, working groups are formed, which are responsible for the different work packages and report to the MB. Responsibilities for the various tasks are given in Table 3, which should be considered as tentative. Due to the very large HISPEC collaboration a final decision can only be taken after the MB has been formed and the next HISPEC collaboration meeting has taken place. External expert advice will be asked for when deemed necessary by the MB.

Table 3: Tasks, responsibilities and intended cooperation with other activities (to be completed at the next HISPEC collaboration meeting and approved by the HISPEC management board).

Task	Group	other LoI
Beam tracking and identification detectors: - Timing scintillators - position detectors - position sensitive ΔE det. - ΔE/E calorimeter - magnetic spectrometer (upgrade) - associated vacuum system	GSI GSI	Decay, R3B
AGATA γ spectrometer	AGATA collaboration	R3B, EXL
HYDE charged particle array	Sevilla, Huelva	
Ancillary detectors: - neutron array - BaF array - light charge particle array - plunger - Orange spectrometer	 Milano, Studsvik Lund Köln Köln	Decay
Electronics and data acquisition - beam detectors - AGATA - Ancillary detectors -	GSI AGATA collaboration	NUSTAR
Simulation and modelling	Valencia	
Analysis software	Kracow	NUSTAR
System integration	GSI	NUSTAR

5.5 Time schedule

It is intended to develop the beam detectors and part of the ancillary detectors well in advance of the commissioning of the Low Energy Branch to be able to employ them already at the FRS. The fast SIS ramping will provide a major short term beam intensity increase. Therefore an early start with improved experimental equipment is considered highly beneficial not only to gain experience but also to perform outstanding experiments.

Table 4: Time plan

Task/Milestone	Period
R&D on AGATA	2003-2007
AGATA demonstrator ready for tests and experiments	2007
4π AGATA array ready	2012
R&D on particle identification detectors	2004-2008
Software development	2004-2009
Data acquisition system	2004-2009
Technical Report	end of 2004
Technical Design Report	end of 2005

5.6 Beam time considerations

To make best use of the AGATA array, which will be shared between host laboratories, experimental campaigns are anticipated with a duration of 6 to 12 months. During these campaigns a major fraction of the available beam time will be asked for. The HYDE detector can be used in stand-alone mode for reaction studies when AGATA is not available. Predominantly highest primary beam intensity and duty cycles optimized for highest integral yield are required.

References

1. AGATA Technical Proposal, ed. J. Gerl and W. Korten; GSI Darmstadt 2001.
2. M. Hass et al., Phys. Rev. C 41 (1991) 2140.
3.T. Glasmacher, Annu. Rev. Nucl. Part. Sci. 48, (1998) 1.
4. RISING proposal GSI Darmstadt (2002) and H.J. Wollersheim et al., Nucl. Instr. Meth. (submitted)
5. O. Kenn et al., Phys. Rev. C63 (2000) 021302.
6. N. Benzer-Koller et al. Annu. Rev. Nucl. Part. Sci. 30 (1980) 53.
7. R.S. Simon et al, Z. Phys. A 325 197 (1986).
8. M. Leino and F.P. Heßberger, Ann. Rev. Part. Sci. subm. for publ.

Letter of Intent
for

Decay spectroscopy with implanted beams

DESPEC Collaboration

April 7, 2004

Abstract

The access to the first structure information of the most exotic nuclei will be possible with the implanted beams into the active stopper detector. The subsequent α, β, γ, proton and neutron decays of those species will be measured with a compact multi task array consisting of double sided silicon strip detectors, germanium γ-ray detectors and neutron detectors. The main objective of this LoI are the doubly magic nuclei placed at the extremes of the chart of nuclides, as ^{100}Sn, the new magic numbers and shell evolution for the very neutron rich isotopes e.g. ^{120}Zr, and exploration of astrophysical r- and rp-process paths. The necessary development of the new detector, electronics and data acquisition techniques will be undertaken within this project.

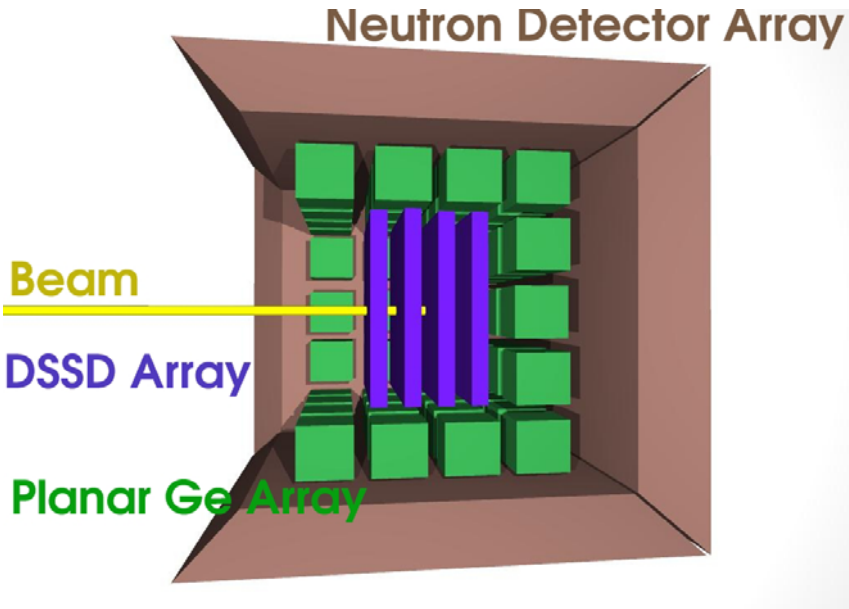


Fig. 1: Schematic top-view of the experimental set-up for "complete" spectroscopy with stopped beams. This set-up which has a length of 7 m including the beam tracking will be situated in the Low Energy Cave.

List of the Collaboration

Bordeaux (B. Blank)
Daresbury (J. Simpson)
Darmstadt (M. Górska, J. Gerl, C. Scheidenberger et al.)
Debreceen (A. Algora)
Edinburgh (P.J. Woods)
Giessen (W. Plass)
Jyvaskyla (J. Äystö, A. Jokinen, M. Leino, H. Kettunen, H. Penttilä, C. Scholey, J. Uusitalo)
Leuven (M. Huyse)
Liverpool (R. D. Page)
Louvain-la-Neuve (C. Angulo)
Lund (D. Rudolph)
Köln (J. Jolie, P. Reiter et al.)
Krakow (A. Maj)
Madrid (A. Jungclaus)
Mainz (K.-L. Kratz)
München (T. Faestermann, R. Krücken)
St. Petersburg (L. Batist)
Stockholm (A. Johnson et al.)
Surrey (P. Regan, P. Walker)
Uppsala (H.Mach)
Valencia (A. Algora, B. Rubio)
Warsaw (M. Pfutzner)

Conveners: P. J. Woods (Edinburgh), B. Rubio (Valencia), K.-L. Kratz (Mainz), M. Górska (Darmstadt)

Corresponding author: pjw@ph.ed.ac.uk;

Content

1. Physics case

Decay studies lie at the very frontier of the field of exotic nuclei, since once the existence of an isotope has been demonstrated, the next elementary information we seek is how it decays. Experiments can be performed with very high sensitivity and key physical information can be gleaned from a relatively small number of events. The Super FRS system will allow the fast (<=100ns), efficient transportation of short-lived exotic nuclei, with clean in-flight particle identification.

A unique feature of the FAIR Super-FRS facility will be the access to new regions of neutron-rich exotic nuclei produced by the fission of high intensity, high energy ^{238}U beams. A recent US Government panel identified the 10 most outstanding questions in astrophysics. One of these was an understanding of rapid neutron (r-process) nucleosynthesis of heavy elements in supernova explosions, which remains poorly understood. Pioneering studies by the Mainz group and collaborators have provided the first limited access to decay studies in regions of the r-process around the expected waiting points. At FAIR studies of very neutron-rich exotic nuclei lying along whole new swathes of the r-process path will be possible. The key physical information sought from these nuclei are the β-decay half-life, β-delayed neutron branching ratios, and neutron separation energies. Decay studies using the highly efficient Super-FRS with implantation detector systems will be able to address the first two issues. Such studies will also be vital to provide valuable information on the development of nuclear structure between β-stability and the r-process path, as well as the first insights into the evolution of shell structure towards the neutron drip line. This is of particular importance for the mass regions before and after the classical magic neutron numbers 50, 82 and 126 where phase transitions may occur associated with new magic numbers. This is a key issue for both nuclear structure and astrophysics. Measuring the β-decay of Z=40, N=70 ^{110}Zr - possibly replacing Z=40, N=82 ^{122}Zr as the neutron-magic r-process waiting point isotope - and the heavier isotopes towards ^{122}Zr would be a key test of N=82 shell quenching and the predicted development of new shell gaps very far from stability. Highly sensitive studies of γ decays of high spin isomers of implanted isotopes offer a unique window on the shape and shell structure of very neutron-rich nuclei, with implantation techniques permitting the measurement of nuclear spins and moments in perturbed angular correlation experiments. In the course of such studies of very neutron-rich nuclei it will be sensible to be open to exotica - in particular, high spin isomeric states may provide the first laboratory for studies of the previously unobserved one and two neutron radioactivity decay modes.

The interplay between explosive astrophysical scenarios (novae, X-ray bursters etc.) and the properties of exotic nuclei is also very much in evidence on the proton-rich side of stability. Here, waiting points are created by the proton drip-line - the β-decay half-lives of several key nuclei lying along the rp-process path are unknown, or imprecisely determined. In very extreme scenarios it is possible that these waiting points could be bridged by two proton capture reactions, in which case a knowledge of the intermediate odd Z proton unbound system is necessary. This can only be achieved through β-delayed proton studies of the decay of the highly exotic even Z precursor nucleus. Although the proton drip-line is largely mapped for odd Z-nuclei up to Z =83, the limit of particle stability for even Z nuclei is only established up to ^{45}Fe, the only known example of ground-state two proton radioactivity. The Super-FRS facility will have the capability of accessing the (2-) proton drip-line for much heavier even Z nuclei, where many more examples of ground-state two proton radioactivity must exist. There is immense theoretical interest in this exotic decay mode, with distinctly different decay rates predicted for competing decay mechanisms. The new facility will allow an exciting exploration of two proton radioactivity across a panorama of nuclear shapes and shells.

α-decay remains a very important tool for discerning the ground and low excitation energy properties of the nucleus - the dramatic demonstration of triple shape co-existence of 0^+ states in neutron-deficient Pb isotopes, has mainly been based on α and conversion electron spectroscopy measurements. Furthermore, alpha-decay measurements can be used to extrapolate significantly beyond the known mass surface and therefore will be highly complementary to the mass measurement programme at the new facility (see Advanced Trap and ILIMA LoIs). A high priority for the new facility will be the exploration of nuclear structure around doubly-magic ^{100}Sn. Very high α-decay reduced widths are found in the

region around ^{100}Sn - a particularly important test of the double shell closure will be a measurement of the alpha-decay reduced width of ^{104}Te, which should have a lifetime in the range 10-100 ns. The vastly improved particle production rates and rapid transportation of the Super-FRS should permit a direct identification of ^{104}Te. The half-life could be determined by studying the rapid triple α cascade from ^{112}Ba to ^{100}Sn using digital spectroscopy techniques.

Increased particle yields will also enable a first high precision β-decay study of ^{100}Sn. β-decay is a process governed by a very simple, selective operator, and therefore provides a sensitive test of the theoretical description of the ground state of ^{100}Sn and other nuclei. The same β-decay operator governs charge exchange reactions at L=0 momentum transfer. Studies of β^+ decay strengths, and (p,n) charge exchange reactions on the same nucleus at the high energy branch of the Super-FRS will allow us to test and exploit the Ikeda sum rule. Isospin symmetry can be tested in studies of the β-decays of mirror nuclei, and β-decays provide a tool for exploring the strength of T=0 and T=1 pairing effects in nuclei. One long-standing problem is the issue of Gamow-Teller quenching in nuclear β-decays. For highly exotic isotopes, with large β-decay Q-values, it will be possible to make detailed comparisons between full-scale shell model calculations and experimental studies of β-decay strength functions. On a more fundamental level, high particle yields will allow precision half-life measurements of superallowed Fermi transitions in nuclei such as ^{62}Ga. Such studies can be used to explore issues such as the unitarity of the CKM matrix in the Standard Model of the electroweak interaction. These studies will be complemented by work on high precision mass measurements (to determine β-decay Q-values) using the ion trap system.

2. Experimental Setup

All of the experiments anticipated within this LoI involve implantation prior to decay. In most cases this will involve an active solid state detector system. There is a particular need for such a system to correlate implanted ions and subsequent generations of charged particle (β , p, α) decays where high rates can be expected or long correlation times are needed. In general, such measurements will also require high energy resolution both for signal to background discrimination, and because the physics (eg 2p-decay studies) demands such precision for comparison with theory.

It is important to emphasize, that while as much commonality as possible should be sought for global decay spectroscopy set-ups, the varied nature of these experiments means a flexible, modular approach as described in the following is desirable to dovetail in an optimum manner the experimental set-up with the requirements of individual experiments.

2.1 Detector performance

Double-sided Silicon Strip Detector (DSSD) system is ideal for the purpose of discriminating between implanted ions and subsequent decays. It will benefit from the improved range localization provided by the energy focusing device on the Super-FRS. Such a system needs to be sensitive to short-lived (~ μs) decays under conditions of extreme overload following implantation. This means that pre-amplifier systems with fast transistor reset systems will be needed for multi-channel set-ups. By the time the Super-FRS is in operation the per-channel cost of digital spectroscopy systems should have become more reasonable and we would anticipate that multi-channel DSSD systems would be fully instrumented with transistor reset pre-amplifiers and digital spectroscopy systems. Triggerless Data Readout (TDR) systems have been developed at Daresbury, CCLRC for use with the GREAT system at Jyväskylä. Such systems can be helpful in delaying the decision making process on which events are of interest - a useful feature when detectors are firing at vastly different rates. It is anticipated that a similar system would be developed for data acquisition purposes using DSSD set-ups on the Super-FRS.

Gamma ray detector arrays
In nearly all such se-tups it will be sensible to incorporate high efficiency, highly segmented Ge γ-ray detection systems close packed around the stopped ions. An array based on planar Ge detectors or VEGA type Ge detectors in combination with other Cluster type detectors will be the most applicable. The upgrade of the VEGA array is the easiest solution from the perspective of today. However, a planar Ge array is much more compact and can be used in combination with other large detectors, e.g. liquid scintillators for neutrons. Therefore the development task of a planar Ge array will be undertaken. The high efficiency of such an array ($\varepsilon_\gamma \sim 0.3$) and large granularity of segmented crystals in combination with modularity and mobility for different experimental needs will provide a set-up particularly well suited for low and medium γ-ray multiplicity applications.

Double-sided Germanium Strip Detectors
Double-sided Germanium Strip Detectors are an interesting option and have a high polarization sensitivity - such systems are already in use on the GREAT spectrometer at Jyväsklä, and at Argonne. Again it may be desirable to incorporate transistor reset systems into the Ge detector design in order to cope with the immediate γ flash following ion implantation. Since the ions are stopped, a ray tracing capability is not essential for recovery of energy resolution through Doppler broadening, although high granularity is still desirable to cope with potentially high rates and to avoid summing. In certain cases, where high efficiency is at a premium (β -strength function studies, positron background rejection etc.) it may be desirable to replace Ge systems with BGO or NaI systems. Thought should also be given to extending the technique for studying decays of μs-isomers to incorporate conversion electron studies.

BaF_2 array
The fast timing response of BaF_2 detectors can be used for lifetime measurements for states with lifetimes longer than ≈10ps. The lifetime of a given excited state is determined by measuring electronically the time difference between the populating and depopulating transitions, detected by two (or more) BaF_2 crystals. Using BaF_2 detectors lifetime measurements can be carried out for stopped radioactive ions, as opposed to Doppler shift techniques. This is particularly important when the nuclear state of interest is populated following the decay out from an isomeric state (or beta decay). Large BaF_2 crystals can be used to measure high energy γ rays with a much higher efficiency than with Ge detectors.

Neutron detectors
As described above, the measurement of the decays of r-process nuclei will be a particularly high scientific priority. An especially important requirement will be the development of modern high efficiency neutron detector arrays for measurements of dominant β -delayed one or multi-neutron branches, and of β-n-γ–coincidences to reach levels in the A-1 (-2, -3) nuclei inaccessible by β-γ–spectroscopy of the initial delayed-neutron precursor isotopes of mass A. Furthermore, it would also be important to develop high energy resolution neutron detector systems for spectroscopic studies of β -delayed neutron emitters in the r-process path with $S_n \sim$ 1-3 MeV, and searches for 1 and 2 neutron radioactivity.

3. Trigger and Data-Acquisition System

The data acquisition system will be used for the tracking and beam identification detectors, and will be realized within the framework of the common NUSTAR DAQ concept. The various component detectors will usually run with dedicated data acquisition systems. If appropriate, the system will use common master triggers, otherwise total data readout is foreseen. A time stamp technique will be used to merge the data of the different systems.

4. Physics Performance

A simulation software will be developed on the basis of which feasibility demonstrations for the specific reaction studies of interest can be provided in a conceptual design report. In parallel, prototype detectors will be built and tested, the electronic read-out techniques be developed, the time line being given below. The RISING project is at this moment operational at GSI. With RISING the basic concept of high resolution γ spectroscopy in combination with an active implantation detector for the heavy ion beams will be utilized in 2005. However, a lot of experience has been already gained with the precursor experiments performed at GSI within the VEGA collaboration and at GANIL. On the other hand detectors proposed in this LoI are intended to be used at the current RISING set-up to gain experience and to perform improved experiments at the upgraded FRS. In this sense high resolution spectroscopy towards the set-up proposed in this LoI is seen as an evolutionary development.

5. Implementation

5.1 Experimental area

The space requirements for the separate beam line in the Low Energy Cave where the set-up should be mounted amounts to 7 m length including the tracking detectors for beam identification, and 4 m width. However, if AGATA and the stopped beam array will be combined (e.g. in decay tagging experiments) additional space of 4 m length will be required behind the planned magnetic spectrometer. Access to all parts of the set-up is essential to exchange, maintain and reconfigure detectors. Standard electrical power, cooling water and liquid nitrogen infrastructure is required. As common for all the set-ups in the Low Energy branch detector storage, maintenance and development area with liquid nitrogen supply and exhaust absorbing stands is also desirable.

5.2 Radiation environment

The radiation environment will be similar to other branches of the Super-FRS dealing with fast moving heavy ions. The stopping of ions involves radiation which is typical for ions passing trough the matter. The proposed setup will deal with lowest beam intensities.

5.3 Cost estimate

Estimates include instrumentation, electronics and data acquisition. Buildings, beam lines and general infrastructure are not taken into account. Beam tracking and identification detectors are not included as they are part of the HISPEC LoI.

Table 1: Cost estimate for the investment

Item	Cost estimate (M EUR)
DSSD detector	0.5
GREAT type detector	1
Ge detector array	3
Neutron detector array	0.5
Total	**5.0**

5.4 Organisation and responsibilities

All of the research teams have experience with regard to scientific or technological aspects addressed in this LoI and will participate according to their expertise and physics interests. Participating groups have performed decay experiments at the FRS, are developing and running the RISING project at GSI or are involved in the EXOGAM project at SPIRAL (Ganil).

A Management Board (MB) will be formed out of representatives of the participating groups taking over major duties in developing the detector system. At its next meeting, the MB will name the spokesperson and deputy of the collaboration. The main duties of the MB are to monitor the progress of the project and the quality of the developments, to ensure the reporting procedure according to the demands of the International facility at GSI as well as publication of results, and to guarantee optimal communication between the participants and thus economical usage of the provided funding. For monitoring purpose, the MB will request internal reports from the participants at regular intervals.

To guarantee that various components of the project are properly dealt with, working groups are formed, which are responsible for the different parts and report to the MB. Responsibilities for the various tasks are given in Table 2 which should be considered as tentative until a final decision will be taken after the MB has been formed. External expert advice will be asked for when deemed necessary by the MB.

Table2: Tasks and responsibilities

Task	Group	Contact
DSSD detector	Edinburgh	P. J. Woods
GREAT type detector	Liverpool	R. D. Page
Ge detector array	Valencia, GSI	B. Rubio, M. Górska
Total absorption spectrometer (TAS)	St. Petersburg, Valencia	L. Batist, A. Algora, B. Rubio
Neutron detector	Mainz	K. - L. Kratz
Electronics and data acquisition	to be appointed	to be appointed
Simulation and modelling	to be appointed	to be appointed
Analysis software	to be appointed	to be appointed
System integration	GSI	M. Górska, Ch. Scheidenberger

5.5 Time schedule

The research and development period for all the detector components should finish before 2007. However, some parts of the set-up will be ready for tests and experiments earlier. The technical report will be written till the end of 2004. The technical design report will be available end of 2005. The data acquisition and software development will be carried on in the period 2004-2008. The whole system should be ready for first experiments with the upgraded FRS spectrometer from 2008.

5.6 Beam time

The whole set-up should be permanently set up at FAIR (e.g. to check rare beam settings of the Super-FRS for other experiments). Experimental campaigns of 3-4 weeks will be planned for the combined experiments with a similar topic and/or setup requirements.

Letter of Intent
for

Precision Measurements of very short-lived nuclei using an Advanced Trapping System for highly-charged ions

MATS Collaboration

April 06, 2004

Abstract

We propose high-precision mass measurements and trap assisted spectroscopy of short-lived radio nuclides using an advanced trapping system and highly-charged ions. Trapping devices are versatile tools for nuclear physics experiments with radioactive ions and are becoming more and more important at accelerator facilities. The proposed setup will allow mass measurements on radio nuclides with a so far unrivaled accuracy. The mass is one of the most fundamental properties of a nuclide, being a unique "fingerprint", and its measurement contributes to a variety of fundamental studies including tests of the Standard Model and the weak interaction.

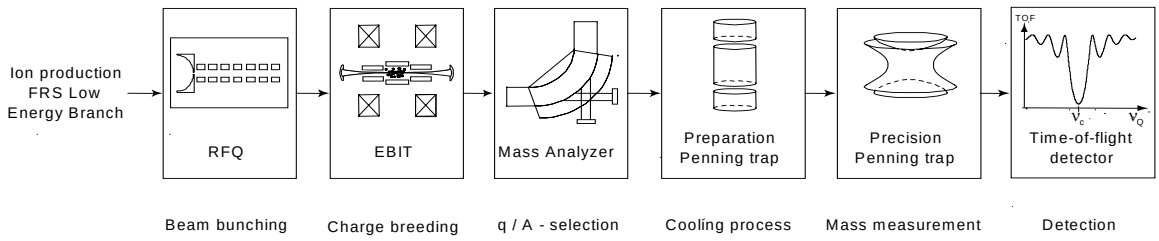


Fig. 1: Schematic view of the components of the MATS set-up which will be located in a 8 x 3 m^2 area in the Low Energy Cave.

List of the MATS Collaboration

CSNSM-IN2P3-CNRS, F-91405 Orsay, France,
G. Audi, D. Lunney, C. Guénaut

Ernst-Moritz-Arndt Universität Greifswald, D-17487 Greifswald, Germany
A. Herlert, G. Marx, L. Schweikhard

Friedrich-Alexander-Universität Erlangen-Nürnberg, 91054 Erlangen, Germany
P.-G. Reinhard

GSI-Darmstadt, D-64291 Darmstadt, Germany
M. Block, H. Geissel, F. Herfurth, Yu.A. Litvinov,
M. Matos, Yu. N. Novikov, C. Scheidenberger, M. Winkler

Johannes Gutenberg-Universität Mainz, D-55099 Mainz, Germany
K. Blaum, I.Bloch, C. Weber

Justus-Liebig Universität Gießen, D-35390 Gießen, Germany
W. Plass

JYFL University of Jyväskylä, P.O. Box 35, Jyväskylä, Finland
J. Äystö, A. Jokinen, S. Kopecky, Iain Moore, A. Nieminen

Lawrence Livermore National Laboratory, Livermore, CA 94550-9234, USA
D. Schneider

Ludwig-Maximilians-Universität München, D-85748 Garching, Germany
D. Habs, S. Heinz, O. Kester, J. Szerypo, P.G. Thirolf

MPI Kernphysik, 69117 Heidelberg, Germany
J. Ullrich, J. R. Crespo López-Urrutia

University of Brussel,1050 Brussel, Belgium
P.-H. Heenen

Seattle University, Seattle, WA 98122-4340, USA
M. Bender

Stockholm University, SCFAB, S-10691 Stockholm, Sweden
T. Fritioff, R. Schuch

Convenors Klaus Blaum, Univ. Mainz, Germany **corresponding author**
Email: blaumk@uni-mainz.de
J. R. Crespo López-Urrutia, MPI Heidelberg, Germany
Email: crespojr@mpi-hd.mpg.de

Deputy and **GSI contact person**: Frank Herfurth, GSI Darmstadt, Germany
Email: f.herfurth@gsi.de

Table of contents

1. Physics case

1.1 Introductory note

In the Letters of Intent "SPARC" and "HITRAP" it is also proposed to study highly-charged ions for atomic-electron binding energies, QED tests and similar, however in a complementary way yielding levels of accuracy of the order of 10^{-10} and better.

1.2 Introduction and overview

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 only limited by the half-life of the radionuclide of interest. Second, the ion beam performance can be improved by, *e.g.*, ion accumulation and bunching, which allows an effective use of rare species. Third, stored ions can be cooled and manipulated in various ways, even polarization and charge breeding of the ions are possible.

It must be noted that these approaches are complementary to the ones pursued at the other branches of the Super-FRS, having specific advantages and unique capabilities rather than leading to a duplication of efforts. For instance, precision measurements in ion traps provide the most accurate mass values, which are needed as calibration points for the ILIMA program proposed for the storage ring branch. There, the program aims at mapping the mass surface and looking for nuclear structure effects, whereas here atomic masses can be measured with the highest possible precision, which opens up new fields such as probing the Standard Model to the highest levels of accuracy.

1.3 Research objectives

Mass measurements at the Low-Energy Branch of the Super-FRS offer the unique possibility to extend our knowledge of masses by several nuclides in the region around the doubly magic nuclei ^{78}Ni and ^{132}Sn. In these regions the knowledge on nuclides and their properties is very limited and many masses far away from stability are still unknown and will remain unknown in the next years. New phenomena as for instance shell quenching may arise, the closeness of the continuum and a reduction of spin-orbit splitting being two of several competing possible reasons [Dob96]. The yields available at the Super-FRS for neutron rich nuclei provide an excellent opportunity for high-precision mass measurements in these mass regions where many nuclides can be addressed for the first time. In addition, high-resolution and high-precision measurements are required in the case of low-lying isomeric states to make a clear identification, e.g. to resolve the discrepancies between theoretical predictions and experimental data for the ground and first isomeric state in ^{131}Sn [Fog99]. Recent shell model calculations [Bro02] showed, that the first isomeric state should be at about 50 keV, which is much less than the accepted value of about 250 keV and still lower than earlier predictions of less than 140keV [Gen99]. To resolve such states a resolving power of above 10^7 is required which can be easily reached while using highly-charged ions. The accurate masses will serve as reliable calibration points for mass measurements planned at the ring branch. At the present SIS-18 facility such measurements suffer from inaccurate or even wrong mass values, which were mostly obtained using decay-spectroscopy techniques.

Very precise mass values with uncertainties of the 10^{-8}-level or even better for specific unstable nuclides are important to test symmetry concepts in nuclear physics and to uncover physics beyond the Standard Model (SM) of particle interaction. Examples are the isospin symmetry, which allows very precise mass predictions using the isobaric-multiplet mass equation IMME, the search for scalar currents that are not predicted in the SM by precision beta-neutrino correlation experiments, and a test of the conserved-vector-current hypothesis, a postulate of the SM. The mass accuracy needed in these cases is only achievable with direct mass measurements in Penning traps.

2. Experimental techniques

2.1 Experimental setup

We propose a novel combination of an electron beam ion trap (EBIT) and a Penning trap mass spectrometer at the Low-Energy Branch of the Super-FRS, which exploits the advantages of highly-charged ions for high-precision mass measurements. A schematic drawing of the proposed combination is shown in figure 1.

A major advantage of the EBIT consists in the possibility of spectroscopic measurements during the charge-breeding time. High-resolution spectrometers in the x-ray, VUV and visible region can collect data used to determine the fine and hyperfine structure of the ions [Bei98, Cre96, Cre98, Bei01] in the trap. These methods have been refined in the last decade and yield information not only on the atomic structure, but on isotopic shifts [Tup03] and nuclear size effects such as magnetization distribution as well. The Heidelberg charge-breeding EBIT will also be tested with the current EBIT laser spectroscopy setup at MPIK.

2.2 Mass measurements

The mass measurement of an ion confined in a Penning trap is carried out via a determination of the cyclotron frequency $\nu_c = qB/(2\pi m)$, where q and m are the charge and the mass of the ion and B is the magnetic-field magnitude. The mass of an ion is obtained from the comparison of its cyclotron frequency ν_c with that 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). The advantage of using highly-charged ions becomes immediately obvious since the cyclotron frequency scales linearly with the charge 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 accuracy scales with the resolving power. The relative statistical mass uncertainty is then given by

$$\delta m/m \approx m / (T_{ex}\, q\, B\, N^{1/2}) \qquad (1) \qquad \text{(SI units)}$$

where N is the number of detected ions. In order to obtain a high accuracy, *i.e.* a low mass uncertainty, high cyclotron frequencies through strong magnetic fields or high charge states, and long observation times are desirable. For radioactive ions far from stability the observation time is limited by the half-life while the number of detected ions is depending 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 as compared to the case of singly-charged ions, which gives access to very short-lived nuclides. Figure 2 shows the advantage of using highly-charged ions with respect to the accuracy in the case of an ion with mass 100 in a 7 T strong magnetic field.

For the Penning trap system a superconducting magnet of 6 to 9 T with field homogeneity of 10^{-7}-10^{-8} in the two trapping regions is required. For the detection, i.e. the observation of the masses of the confined ions, either a Fourier Transformation Ion Cyclotron Resonance (FT-ICR) method [Sch92] or a Time-of-Flight (TOF) method [Grä80] can be used. Whereas the observation of the image currents is non-destructive, the TOF detection of the cyclotron resonance is destructive.

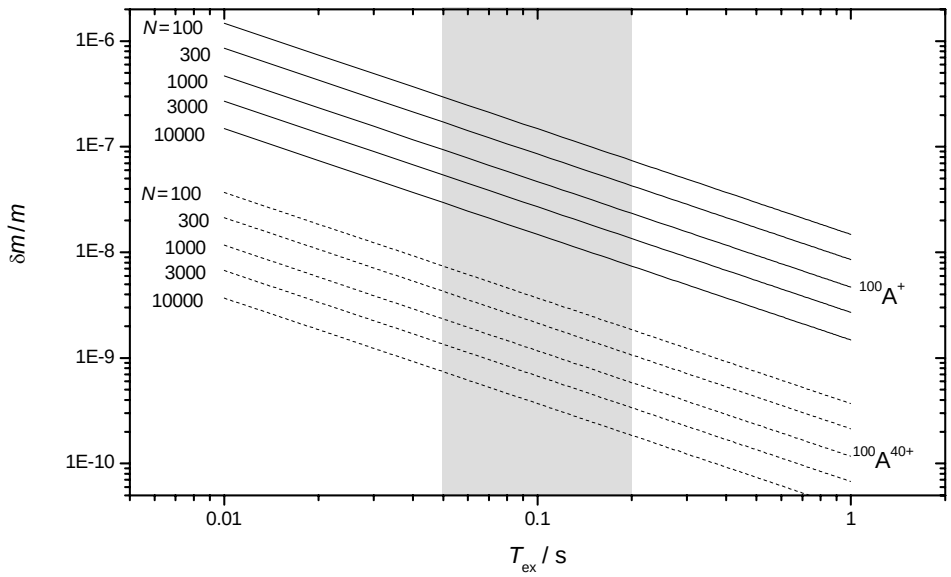


Figure 2: The achievable mass uncertainty (see Eq. 1) for a nuclide with mass A = 100 u as a function of the excitation time in the Penning trap (B = 7 T) for two sets of charge states and different numbers of detected ions. The upper set of curves belong to singly charged ions, the lower set of curves to ions in the charge state 40+. The grey shaded area corresponds to an excitation time T_{ex} of 50-200 ms.

2.3 Charge breeding

At present the only electron beam ion source trap in operation for charge breeding of short-lived radionuclides is REX-ISOLDE/CERN for post-acceleration experiments.[1] With a 5 keV electron beam and a current of 0.5 A a current density of >200 A/cm^2 throughout a 0.8 m long trap region can be obtained in the charge breeder. With these parameters *e.g.* the REXEBIS trap at ISOLDE/CERN can hold ~6x10^9 charges for an electron-beam charge-compensation of 10%. 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 Tab. 1. Figure 3 shows the breeding time as a function of charge state for some selected elements.

Table 1: Peak charge-state after 20 ms breeding time.

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

[1] Another facility is planned in the framework of the TITAN project at TRIUMF, which is also aiming for high-precision mass measurements, but on radionuclides produced at the TRIUMF ISOL facility.

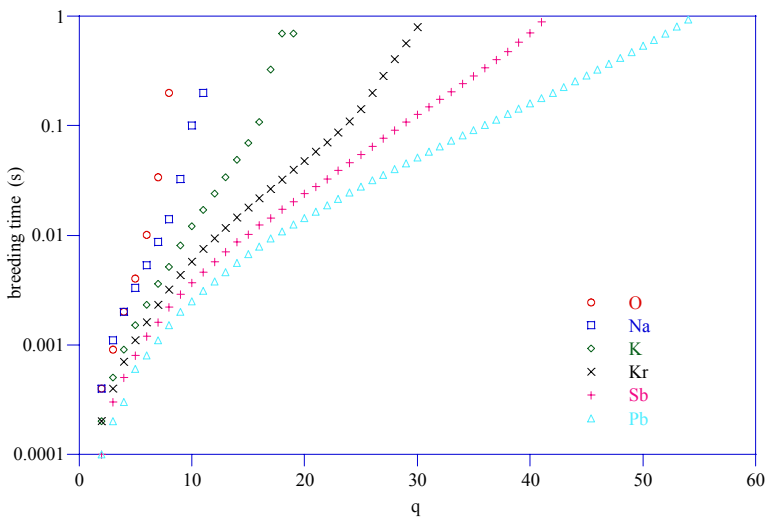


Figure 3: Breeding times as a function of the charge state for a current density of 200A/cm^2 (courtesy of F. Wenander).

Already with such an EBIT an enormous gain is achievable in short breeding times. However, for the proposed setup it is planned to use an EBIT like the device which is currently being built by the Heidelberg group, an apparatus which will be used at the TRIUMF ISOL facility. This machine will operate at 6T with a cryogen-free superconducting magnet. An electron beam current of 5A and the use of a non-immersed gun will result in much higher current density (of more than 10000 A/cm^2), beam energies of up to 60 keV, and much reduced charge-breeding times. This, in turn, allows the study of isotopes with still shorter lifetimes than the currently proposed techniques. Although the total trap length is reduced by a factor of two, the increased current yields a higher number of stored ions than the REX-EBIS setup. Furthermore, the application of dielectronic recombination resonances for the purification of the main charge state of the trapped ions [Cres03] results in an increase of the effective yield and in a reduction of the background. For the Low-Energy Branch EBIT, a high-energy beam of 300 keV should also allow the production of hydrogenic ions of the heaviest available elements.

For the aforementioned reasons, we want to configure the charge-breeding EBIT at the Low-Energy Branch with the corresponding spectroscopic diagnostic tools, as they can deliver valuable information on the nuclear structure. A laser spectroscopy laboratory directly connected to the EBIT will indeed allow a wide range of new experiments inside of the trap, including nuclear polarization through optical pumping, laser cooling, etc. The necessary techniques are currently under development at the Heidelberg MPIK and should become mature for routine applications in the next two years.

2.4 Trap assisted spectroscopy

Finally, new approaches and an outlook for new developments in this field is given. Presently high-resolution electron spectroscopy is limited by the thickness of radioactive sources due to scattering in the source material. Thus it is intriguing to consider ions localized in a Penning trap as an ideal carrier-free source where energy loss or scattering do not influence the line shape. A cold ion ensemble can be quite precisely localized in the center (the corresponding cyclotron radius is typically of the order of 50µm) e.g. by side band cooling. We therefore propose to perform high-resolution spectroscopy of heavy elements in a Penning trap system with high efficiency, concentrating on α- and electron spectroscopy. Exploiting the isobaric suppression capability of the first stage of the trap system (preparation trap) very pure sources can be obtained. The feasibility of in-trap conversion electron spectroscopy has already been successfully demonstrated at the REXTRAP Penning trap system at ISOLDE (CERN) [WEI02]. The conversion electrons emitted by the trapped ions within a confined cylindric volume are transported by the strong magnetic field of the trap through an ejection diaphragm to a detector placed behind the

trap exit. In addition the 'shake-off' process of electrons can be investigated, since many electrons are emitted via this atomic process that occurs with high efficiency for outer electrons.

The physics goal of such measurements is to develop this new technique for the determination of lifetimes of 2^+ states in order to deduce the quadrupole moments of nuclei in a situation where presently no other experimental access exists, such as for superheavy elements. Knowledge on the deformation parameter β_2 or the quadrupole moment, respectively, are key ingredients for the theoretical description of heavy nuclei. From the α–spectra coincident with the electrons the shake-off process itself can be investigated for K, L, M and N shell electrons. Exploiting the coincidence condition betwen the α–particle and the carrier-free source a better understanding of shake-off processes can be achieved. Since the converted transitions are rotational states, the rotational energy and thus the spin can be inferred from the measured energy of the K and L lines. Therefore significantly more conclusive assignments during the construction of level schemes are achievable with such a technique especially in odd nuclei compared to the presently used α–spectroscopic methods.

In conclusion, the unique combination of an electron beam ion trap to produce highly-charged ions and a Penning trap mass spectrometer for high-precision measurements installed at the Low-Energy Branch of the Super-FRS will yield the most accurate results for masses of short-lived exotic nuclei and allows for a new field of in-trap experiments. Mass uncertainties below 10^{-8} can be obtained, which is at present at no existing trap facility possible. Furthermore, due to the extremely high yield of neutron-rich radionuclides, nuclei can be investigated which are much further away from the valley of stability than what is accessible at present at any other radioactive beam facility. Such a setup will open new ways of studying nuclear properties by x-ray and LASER spectroscopy of trapped ions and decays and transitions with high resolution.

3. Implementation

3.1 Experimental area

Width: 3m Length: 8 m Height: 4 m

3.2 Radiation environment

No special requirements (experiments are performed with only a few ten ions per second)

3.3 Cost estimates

Superconducting magnet (without traps and electronics)	300 kEUR
EBIT	500 kEUR
RFQ cooler and buncher (without electronics)	200 kEUR
Electronics (for traps and buncher)	200 kEUR
Vacuum components (for highly-charged ions)	300 kEUR
Off-line ion source	60 kEUR
TOF-detector (with electronics)	20 kEUR
FT-ICR detector (with electronics)	50 kEUR
SUM	**1.630 kEUR**

3.4 Organisation and responsibilities

Mainz, Greifswald, Jyväskylä, Stockholm: Penning trap system
GSI, Munich: RFQ cooler and buncher
Heidelberg, GSI, Livermore, Seattle: EBIT
Giessen, Mainz, Orsay: Detection system and electronics
Mainz, Munich: Trap assisted spectroscopy

The conceptual layout of the setup and its components will be established as a combined effort with the LASER spectroscopy collaboration in order to efficiently use the available resources and to reach optimum performance and physics capabilities.

3.5 Time schedule

Overall preparation period: 4-5 years
The complete setup can be tested, operated, and optimized off-line with test ion sources.

3.6 Beam time considerations

The setup will be permanently installed at the Low-Energy Branch at GSI. Experimental campaigns of about 4 weeks per year (overall, split in periods of typically one week each) should be envisaged and will be ideally be combined with other experiments using reaccelerated beams and same or similar nuclides.

References:

[Klu03] J. Kluge, K. Blaum, F. Herfurth, W. Quint, Physica Scripta T104 (2003) 167.
[Dob96] J. Dobaczewski *et al*., Phys. Rev. C 53 (1996) 2809.
[Fog99] B. Fogelberg *et al*., Phys. Rev. Lett. 82 (1999) 1823.
[Bro02] A. Brown, private communication (2002).
[Gen99] J. Genevey and J.A. Pinston, private communication (1999).
[Bei98] P. Beiersdorfer et al., Phys. Rev. Lett. **80** (1998) 3022-3025
[Cre96] J. R. Crespo López-Urrutia et al., Phys. Rev. Lett. **77** (1996) 826
[Cre98] J. R. Crespo López-Urrutia et al., Phys. Rev. **A 57** (1998) 879-887
[Bei01] P. Beiersdorfer et al., Phys. Rev. A **64** (2001) 032506
[Tup03] I. Tupitsyn, et al., Phys. Rev. A **68** (2003) 022511
[Cres03] J. R. Crespo López-Urrutia et al., Rev. Sci. Inst., accepted (2003)
[Sch92] L. Schweikhard *et al*., Int. J. Mass Spectrom. Ion Proc. 120 (1992) 71.
[Grä80] G. Gräff *et al*., Z. Phys. A 297 (1980) 35.
[Wei02] L. Weissman et al., Nucl. Instr. Meth. (2002)

LASER spectroscopy for the study of nuclear properties

LASPEC Collaboration

April 6th, 2004

Abstract

Using advanced Laser spectroscopy methods, nuclear ground state spins, moments, charge radii, of radioactive nuclei can be determined. The optical techniques, based on hyperfine structure splitting (HFS) or isotope shift measurements, yield *model-independent* information about the nucleus. Various experimental methods and concepts are proposed to take advantage of the exotic nuclei provided at low energy, including spectroscopy on trapped, highly-charged ions, which is a new approach for studies of nuclear and isotopic effects with high sensitivity.

Collaboration

CERN, Switzerland
A. Dax

IN2P3-CNRS Orsay, France
F. Le Blanc, D. Lunney, M. Sewtz

GSI Darmstadt, Germany
W. Nörtershäuser, T.Kühl, C.Scheidenberger, M. Tomaselli

JYFL, Univ. Jyväskylä, Finland
J. Äystö, I. Moore, A. Nieminen

LLNL Livermore, USA
D. Schneider

LMU München, Germany
D. Habs, S. Heinz, J. Szerypo, P.G. Thirolf

MPI Heidelberg, Germany
J. Ullrich, J. R. Crespo López-Urrutia

Pacific Northwest National Laboratory, USA
B. Bushaw

Univ. Manchester, UK
P. Campbell, J. Billows

Univ. Tübingen, Germany
C. Zimmermann

Convenors: W. Nörtershäuser (w.noertershaeuser@gsi.de)
J. R. Crespo López-Urrutia (crespojr@mpi-hd.mpg.de)

Deputy and **GSI contact person**: W. Nörtershäuser (w.noertershaeuser@gsi.de)

Corresponding author: W. Nörtershäuser (w.noertershaeuser@gsi.de)

Table of contents

1. Introductory note

The approaches described here to measure moments of the nuclear charge distribution are complementary to other scenarios intended at the new facility, like dielectronic recombination or electron scattering with the eA-collider.

2. Physics case

The optical techniques, based on hyperfine structure splitting (HFS) or isotope shift measurements, yield *model-independent* information about the nucleus [1,2], and the theory of isotope shifts and HFS is sufficiently well understood to yield precise information on the size and shape of nuclei. On-line laser spectroscopy allows one to study the nuclear properties of ground and isomeric states of short-lived, exotic isotopes which are available in only small quantities. The properties that can be studied are

- the nuclear spin I
- the magnetic moment μ_I
- the spectroscopic nuclear quadrupole moment Q_s and
- the changes in the mean-square nuclear charge radius $\delta\langle r^2\rangle$ between isotopes

It should be noted that longer-lived isomers ($T_{1/2}$ > 10ms) are also accessible. These experimental data are highly accurate and the nuclear parameters can be extracted without a need of a nuclear model. Since the model-independent data are collected in long isotopic chains reaching far from the valley of nuclear stability, these data provide clear information on single-particle as well as collective nuclear effects and enable stringent tests of nuclear models. Furthermore, new phenomena might be discovered which do not show up in stable or long-lived isotopes or which can only be detected as deviation from systematic trends of neighboring isotopes. A striking example is the nuclear shape coexistence and shape transition detected by optical spectroscopy in the mercury region.

Today, mainly two laser techniques are applied: Resonance Ionization Spectroscopy (RIS) of neutral atoms and Collinear Laser Spectroscopy (CLS) of neutral atoms and of singly- and highly-charged ions. In general, the first technique offers the highest sensitivity while the second provides the highest resolution. The present limit for the minimum yield for collinear laser spectroscopy is of the order of 100 ions/s and the shortest-lived isotope investigated is ^{11}Li [3] with a nuclear half-life of $T_{1/2}$ = 9 ms. By resonance ionization spectroscopy, the HFS and the IS of radioactive atoms with a nuclear half-life as short as $T_{1/2}$ = 1 ms (^{244f}Am) has been determined at a production rate of about 10 ion/s [4]. In principle, isotopes with shorter ground-state half-lives would still be accessible by laser spectroscopy, which depends only on the production yield and not on the nuclear half-life.

Furthermore, magneto-optical traps are presently applied for atomic structure investigations of radioactive atoms [5]. This demonstrates that they could be used to study nuclear ground-state properties, utilizing the advantages of a localized, concentrated, and cold sample. Another application is the measurement of the β-neutrino correlation via a coincidence measurement of the recoil ion and the β - particle momenta [6,7] or the measurement of the asymmetry parameter of the β-decay of polarized nuclei [8]. Precise measurements of the angular correlations in β-decay allow one to search for new physics beyond the Standard Model, such as scalar, tensor, or right-hand contributions. Radioactive atom trapping has been confined to the alkali elements so far. However, trapping methods have been developed and employed for most of the stable alkaline earth elements, as well as the rare gases, where metastable states have been used. In the future, similar trapping schemes might be developed for other species as well.
Up to now, most of the optical investigations on short-lived isotopes were performed at ISOL facilities where the radioactive products have to diffuse out of the target matrix. Therefore, no or little information is available for nuclides with half-lives of less than 100 ms or for isotopes of elements which do not diffuse out of the target material because they are non-volatile or chemically reactive. Here, the universal, fast and chemically non-selective production technique of projectile fragmentation and fission

as applied at GSI, as well as the increased yields available at the planned new facility, will enable extension of the knowledge of nuclear ground state properties in isotopic chains to regions further away from the valley of nuclear stability. This is illustrated in Fig. 1.

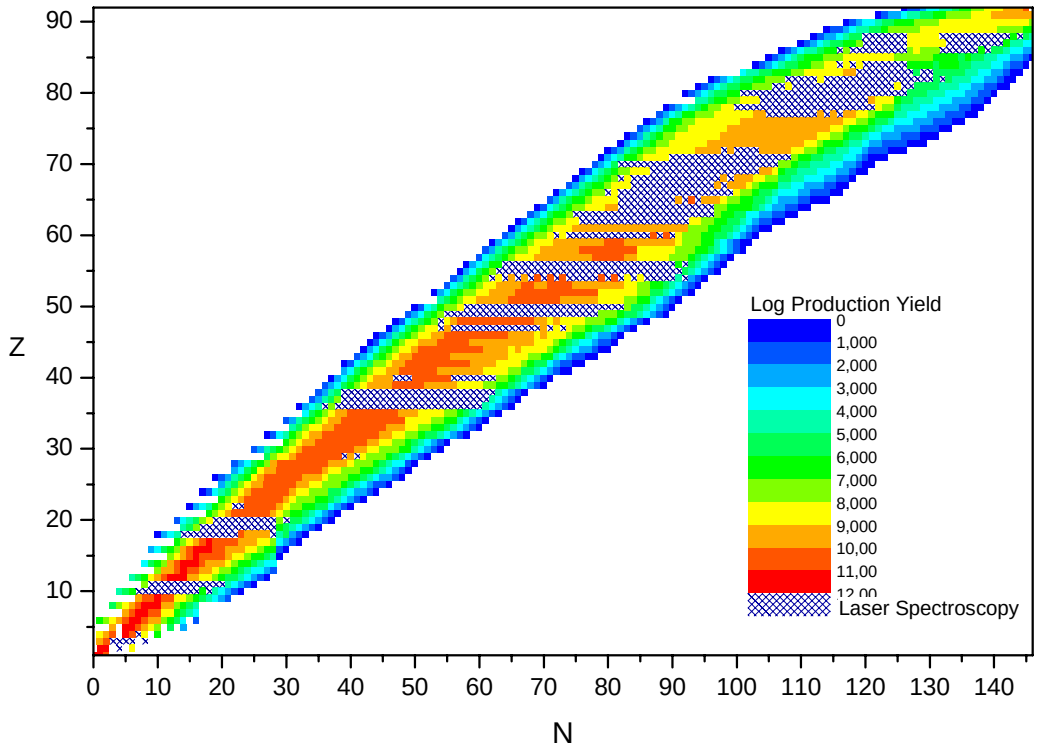


Figure 1: Nuclear chart with expected production yields and regions in which laser spectroscopy has been performed so far.

Here, the expected yields for the different isotopes are plotted and the regions where laser spectroscopy has been performed on chains of radioactive isotopes are indicated. The most interesting regions close to the proton and neutron drip lines have only been reached in few cases. With the exception of titanium, nothing is known from laser spectroscopy on short-lived nuclei in the region of refractory elements around iron (Z = 26) because of the lack of efficient production schemes at ISOL facilities. Similarly, there are gaps in the region of refractory elements around molybdenum (Z = 42) and tungsten (Z = 74). This clearly shows the potential of gathering new information about the ground state structure of nuclei on the Low-Energy Branch at the Super-FRS. Some special regions of interest are:

- the light refractorary region
- high K-isomers
- the octupole region around ^{222}Th
- neutron-rich heavy systems

Table 1 summarizes the possibilities of laser spectroscopy at the Low-Energy Branch.

Table 1: Different laser spectroscopic schemes for radioactive nuclides at the planned GSI facilities. CLS: collinear laser spectroscopy; FS: fluorescence spectroscopy; RIS: resonance ionization spectroscopy; HFS: hyperfine structure; IS: isotope shift; R: resolving power; NAT: neutral atom trap; 1+: singly-charged ions.

Method	Charge state	Detec-tion	Mea-sured	Minimum No. of Particles	Minimum $T_{1/2}$	Reso-lution	Remarks
RIS	Neutral	Ions	HFS, IS	1/s	1 ms	Low	Directly in gas-filled stopping cell
FS (in ion trap)	1+	Photons	HFS, IS	10^4 stored	10 ms	High	Ion trap at room temperature
CLS	Neutral/ 1+	Various	HFS, IS	10^2/s	10 ms	High	After reacceleration to a few 10keV
RIS	Neutral	Ions	HFS, IS	10^4/s	10 ms	Mediu m	Accumulation and desoprtion
FS (in laser trap)	Neutral	Photons	HFS, IS	1 stored	10 ms	High	Restricted to some elements

3. Experimental scenarios

Gas cell: Inside the gas cell **resonance ionization spectroscopy** on the resulting neutral species is possible. The technique has been recently successfully demonstrated for the case of isotope shift measurements of superdeformed isomeric states in Am isotopes [4]. High sensitivity as well as a low half-life limit is obtained on the expense of resolution.

Extracted beams: To the low-emittance ion beams extracted from the stopping cell with an energy of several 10 keV **collinear laser spectroscopy**, resonance ionization spectroscopy, or other optical techniques can be applied on the singly-charged ions or, employing a charge exchange cell, on a fast atomic beam.

Neutral atom trap: such a trap can be used to perform laser spectroscopy with very high resolving power and isotopic selectivity. Presently, the technique is restricted mainly to noble gases and alkalis. Quite a number of atomic transition wavelengths, atomic life-times, HFS and hyperfine anomalies have been determined recently for francium isotopes [9]. Although single-atom sensitivity is reached, the efficiency for loading neutral atom traps has to be increased. This is one of the results expected from the European RTD network NIPNET.

EBIT measurements: The ions stored in the **EBIT** used for charge-breeding can be excited with both pulsed and cw tunable lasers. Forbidden transitions in the visible range have shown a high sensitivity to nuclear-size and QED effects [10,11], which can be exploited in this proposed setup to obtain nuclear spins and magnetization distribution information. Ti-like ions, which can be easily produced in the EBIT, are very amenable to this type of studies due to the flat scaling of the wavelength of the main forbidden line. Other configurations, such as B-like and Be-like, also offer a number of forbidden transitions with a high sensitivity to nuclear and isotopic effects, but with the additional advantage of the simpler atomic structure. In these cases, *ab initio* calculations can be carried out. By using a high-energy electron beam (up to 300 keV), the Low-Energy Branch EBIT should be able to produce hydrogen-like ions of heavy elements. Their ground-state hyperfine transitions have already been studied at the LLNL SuperEBIT [10], although without laser excitation. The application of laser spectroscopic techniques to radioactive trapped ions seems therefore straightforward, and it promises a great increase in experimental precision. The MPIK group is already testing such a setup at the Heidelberg EBIT. The use of laser excitation allows to manipulate the trapped ions through the hyperfine structure of the resonantly excited

transitions. The ions can be also be optically pumped in short times, and nuclear polarization can be achieved in this way. The polarized nuclei can be studied in the EBIT, or extracted from it and delivered to other experiments. Therefore, there is a compelling case for the inclusion of a laser beamline to the EBIT laboratory, or for a dedicated EBIT laser-spectroscopy setup.

4. Implementation

4.1 Experimental Area

The set-up will be installed in the Low Energy Cave.
Width: 3 m Length: 6 m Height: 3 m

Laser Laboratory: ~30 m^2, cooling water and high power connection

4.2 Radiation Environment

No special requirements (experiments are performed with only a few thousand ions per second)

4.3 Cost Estimates

Laser System:	
- Pump laser	150 kEUR
- TiSa	150 kEUR
- Frequency doubler	50 kEUR
- Frequency Stabilization	50 kEUR
Detection System	50 kEUR
Vacuum components	150 kEUR
Optics	50 kEUR
SUM	**650 kEUR**

Note: The costs given here are exemplary for a typical laser system needed for a collinear laser spectroscopy setup mentioned above. Different setups for other experimental opportunities will require a different cost scheme. Moreover, there will be several places at the International Accelerator Facility for Beams of Ions and Antiprotons at GSI, where laser spectroscopy with pulsed or cw-lasers is planned. Some of these setups can certainly be combined and the possibility for fiber transport to different experimental areas should be evaluated. Thus detailed costs cannot be specified at this early stage.

4.4 Organisation and Responsibilities

To be identified. In any case, the conceptual layout of the setup will be established as a combined effort with the Penning trap collaboration(s) in order to efficiently use the available resources and to reach optimum performance and physics capabilities.

4.5 Time schedule

Overall preparation period: ~ 3-4 years
The complete setup can be tested, operated, and optimized off-line with test ion sources.

4.6 Beamtime

The setup will be permanently installed at the Low-Energy Branch. Experimental campaigns of about 4 weeks per year (overall, split in periods of typically one week each) should be envisaged and will be ideally be combined with other experiments using reaccelerated beams and same or similar nuclides.

References

[1] H.-J. Kluge and W. Nörtershäuser, Spectrochimica Acta B 58, 1031-1045 (2003).
[2] E.W. Otten, *Nuclear radii and moments of unstable isotopes*, in *Treatise on heavy-ion science*, D.A. Bromley, Editor. 1989. p. 517-638.
[3] E. Arnold *et al.*, Phys. Lett. B 197, 311-314 (1987).
[4] H. Backe *et al.*, Phys. Rev. Lett. 80, 920-923 (1998).
[5] G.D. Sprouse *et al.*, Nucl. Phys. A 701, 597-603 (2002).
[6] J.A. Behr *et al.*, Phys. Rev. Lett. 79, 375-378 (1997).
[7] A. Gorelov *et al.*, Hyperf. Int. 127, 373-380 (2000).
[8] S.G. Crane *et al.*, Phys. Rev. Lett. 86, 2967-2970 (2001).
[9] J.S. Grossman *et al.*, Phys. Rev. Lett. 83, 935-938 (1999).
[10] I. I. Tupitsyn et al., Phys. Rev. A **68** (2003) 022511
[11] I. Draganic et al., Phys. Rev. Lett. **91** (2003) 183001

Letter of Intent
for

Neutron capture measurements

April 7, 2004

Abstract

Neutron capture cross sections are very important for the understanding of the nucleosynthesis of heavy elements in stars. Maxwell-averaged neutron capture cross sections are needed as input for stellar models; not only for the s process where the production of nuclei is directly proportional to the inverse of its capture cross section, but also for the r and p processes, where the initial abundance distribution is modified by neutron capture reactions during freeze-out. Therefore, we propose an optimized time-of-flight setup at the low energy branch at GSI to measure neutron capture cross sections of radioactive nuclei of relevance for these processes.

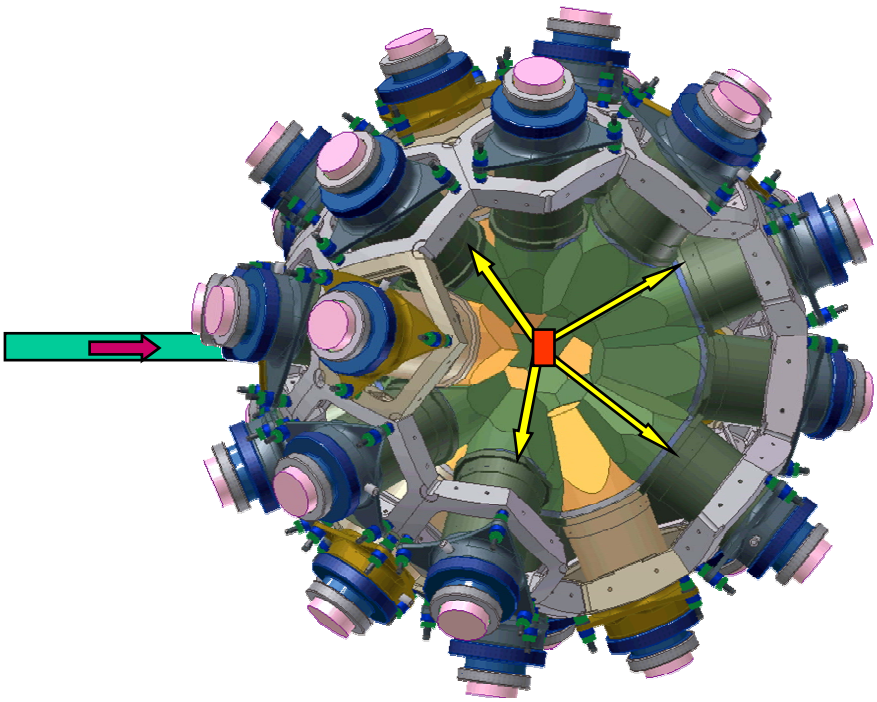


Figure 1: Karlsruhe 4π BaF_2 detector for accurate cross section measurements by detecting the prompt γ-rays after neutron capture. This array together with a compact pulsed 3 MeV proton accelerator will be located in the Low Energy Cave.

NCap-Collaboration

Forschungszentrum Karlsruhe, Germany
M. Heil et al.

ENEA Bologna, Italy
A.Mengoni

INFN Legnaro, Italy
N. Colonna et al.

IFIC Valencia, Spain
J. Tain et al.

Los Alamos National Laboratory, USA
R. Reifarth

University of Notre Dame, USA
M. Wiescher et al.

GSI Darmstadt, Germany
K. Sümmerer, C. Scheidenberger, et al.

Forschungszentrum Rossendorf, Germany
A.Junghans

CEA Saclay, France
F.Gunsing et al.

RCNP Osaka, Japan
Y. Nagai

Oak Ridge National Laboratory, USA
P. Koehler

Convenor: Michael Heil (Michael.Heil@ik.fzk.de)
Deputy and **GSI contact person**: Klaus Sümmerer (k.suemmerer@gsi.de)

Corresponding author: Michael Heil (Michael.Heil@ik.fzk.de)

Contents

1. The physics case

The chemical elements heavier than iron are all produced by neutron capture reactions either by the s process in the late, He burning stages of stellar evolution or by the r process in supernova explosions.

The keV neutron capture cross sections of unstable isotopes play a key role for the interpretation of isotopic abundance patterns caused by branchings in the s-process reaction path as well as for the final r- and p-process abundance distributions originating from nucleosynthesis associated with various phases of supernova explosions. Branchings in the s-process path, which result from the competition between β-decay and neutron capture, yield direct information on the physical conditions of the deep stellar interior and, hence, represent an important test for the corresponding stellar models. Due the extreme temperatures and particle fluxes, the nucleosynthesis paths in supernovae are driven far into the regions of unstable nuclei on both sides of the stability valley. The formation of the final abundance distributions is strongly affected, however, by neutron captures during freeze-out, when the temperature drops below the neutron threshold.

So far, experimental studies in this field of nuclear astrophysics are yet restricted to single cases, mostly based on measurements using the activation method. Successful measurements by means of the more general time-of-flight technique are restricted to very few examples on samples with low specific activities because of the neutron flux limitations of standard experimental configurations. For investigations on rather short-lived nuclei, this limitation must be compensated by the use of samples in the milligram region, which – in turn – implies prohibitive backgrounds from the decay activity of the sample itself.

2. Setup

It is proposed to implement a technique that leads to a drastic improvement of the time-of-flight technique to the point, where measurements can be carried out with microgram samples. This can be achieved by reducing the flight path to a few centimeters by placing the neutron production target of a low energy accelerator right inside of a 4π BaF_2 γ-calorimeter [1] (see Fig. 1), in this way boosting the neutron flux at the sample position by about three orders of magnitude while keeping all advantages of the calorimeter, such as high efficiency and excellent background discrimination. The two essential features of this arrangement (Fig. 2) are that the neutron spectrum can be tailored to the specific energy window of astrophysical interest and that the overall experimental time resolution of 1 ns still provides sufficient resolution in neutron energy for deriving the required cross section average for the stellar neutron spectrum.

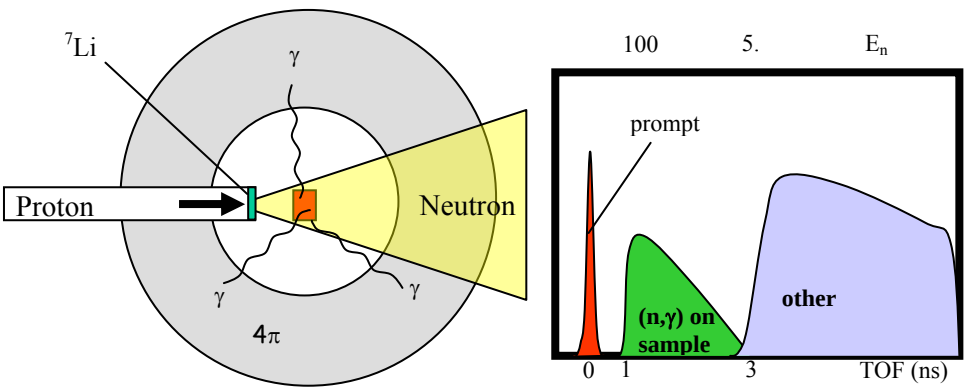


Figure 2 Left: Schematic setup indicating the close geometry between neutron target and sample. Right: Separation of captures in the sample from γ-backgrounds related to the prompt flash and to neutron interactions with the BaF_2 scintillator.

The Low-Energy Branch is ideally suited for the collection of samples from the intense secondary beams available at the Super-FRS, especially since the s-process nuclei of interest are located next to the stability line, where the highest intensities are expected and the collection of samples with several micrograms are feasible.

The technique can be implemented in two steps, which are mentioned already now in order to give a mid-term perspective for this field:

1) Sufficiently long-lived samples ($t_{1/2}$ > 200 d) can be produced and collected at the Low-Energy Branch for measurements at the Karlsruhe Van de Graaff accelerator. Accessible targets for this first step are indicated by bold characters in Table 1.
2) For samples with shorter half lives (10 d < $t_{1/2}$ < 200 d) we propose to install a fast pulsed proton accelerator at GSI for on-site measurements.

As a proof of principle, the proposed setup will be tested with stable samples at the 4π BaF_2 array already existing at Karlsruhe. This phase can be used for optimising the sensitivity of the technique and for an upgrade with flash-ADC readout, which will be mandatory for handling the expected high count rates due to the sample activity. After successful completion of this first part, in the second step a pulsed high-current, low-energy accelerator (total energy 2 to 3 MV, repetition rates 100 to 500 kHz, pulse width <500 ps, peak current >20 mA) should be installed at the Low-Energy Branch at GSI for measurements on site in order to study even short-lived species. This unique combination of on-site sample production and a most advanced setup for neutron capture experiments will open a completely new field of reaction rate measurements on hitherto inaccessible samples, a crucial prerequisite for quantitative nucleosynthesis studies related to explosive scenarios.

The estimated costs are summarized in Table 2. While Step 1 can be realized with minor investments for a Flash-ADC system, Step 2 requires the installation of a suited proton accelerator.

Table 1: Proposed targets and astrophysical motivation (targets with $T_{1/2}$ > 200d, which could be studied in the first step, are indicated by bold characters).

Motivation	Targets
s-process branchings for characterizing the physical conditions during He burning in massive stars and in thermally pulsing low mass AGB stars	**^{36}Cl**, ^{45}Ca, **^{63}Ni**, **^{79}Se**, **^{81}Kr**, **^{85}Kr,** ^{89}Sr, **^{90}Sr,** ^{147}Nd, **^{147}Pm**, ^{148}Pm, **^{154}Eu,** **^{155}Eu,** **^{153}Gd**, ^{160}Tb, **^{163}Ho**, ^{170}Tm, **^{171}Tm**, **^{179}Ta**, ^{185}W, ^{191}Os, **^{204}Tl**, **^{205}Pb**
Explosive nucleosynthesis on the proton-rich side (p-process), explosive Ne/O-shell burning in SN II	**^{55}Fe**, **^{91}Nb**, **^{92}Nb**, **^{93}Mo**, **^{97}Tc**, **^{98}Tc**, ^{103}Pd, **^{109}Cd**, ^{113}Sn, ^{125}I, **^{137}La**, **^{145}Pm**, **^{145}Sm**, **^{148}Gd**, **^{150}Gd**, **^{154}Dy**, **^{172}Hf**, ^{181}W, ^{195}Au, **^{202}Pb**
Explosive nucleosynthesis on the neutron rich side (r-process)	^{32}P, ^{33}P, ^{35}S, ^{45}Ca, ^{60}Fe, **^{106}Ru**, **^{135}Cs**, ^{126}Sn, ^{182}Hf, ^{188}W, **^{194}Os,** **^{210}Pb**

3. Implementation

3.1 Experimental Area:

Step I: Width: 2m Length: 4m Height: 3m
Lab space for sample preparation and storage

Step II: Cave (width ~8m, length ~16m, height ~8m) for the proton accelerator and the irradiation setup (see figure 3)

3.2 Radiation environment

Step I: no special requirements

Step II requires concrete shielding (thickness ~ 1m) for the cave

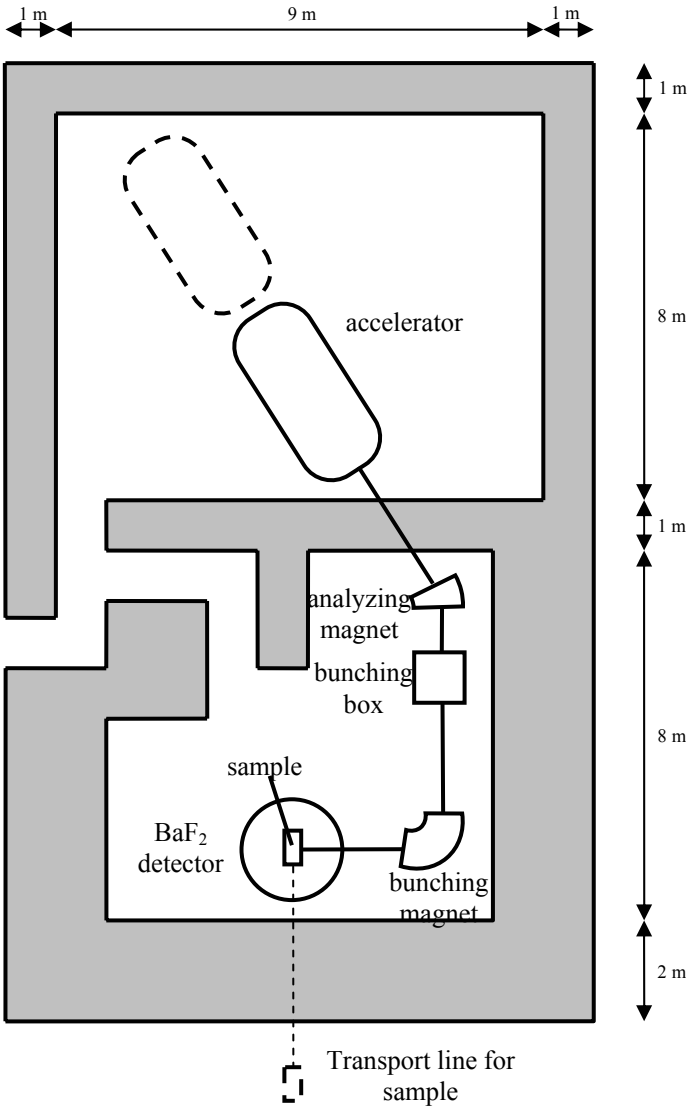


Figure 3: Proposed experimental setup for step II with an accelerator cave and an experimental area.

3.3 Cost estimate

Table 2: Cost estimate

	Items	Estimated costs [k€]
Step I	Flash-ADC system 4π BaF_2 array	100 1.550 (provided by FZK)
Step II	Pulsed proton accelerator	2.600

3.4 Time schedule

The experimental setup available at Karlsruhe can be used for experiments after installation of the flash-ADC-system.

3.5 Beamtime

The setup will be permanently installed at the Low-Energy Branch at GSI. The time for sample collection depends on the available yield for a specific nuclide (typically of the order of ~1 day). It is requested to collect several samples per year (typically of the order of 10), ideally in one bunch. Beamtimes should be combined with other experiments using reaccelerated beams and same or similar nuclides. Fast extraction from SIS100/300.

References

[1] R. Reifarth *et al.*, Nucl. Instr. Meth. A (in press).

Antiprotonic radioactive nuclides

Exo+pbar Collaboration

April 6th, 2004

Abstract

It is proposed to use antiprotons as hadronic probes for exotic nuclei, in particular for the neutron and proton distributions near the nuclear surface. Emitted X-rays and pions from the annihilation allow to study the formation process itself and also the properties of antiprotonic radioactive nuclides. Such experiments with short-lived exotic nuclei and simultaneously trapped antiprotons are hitherto unprecedented.

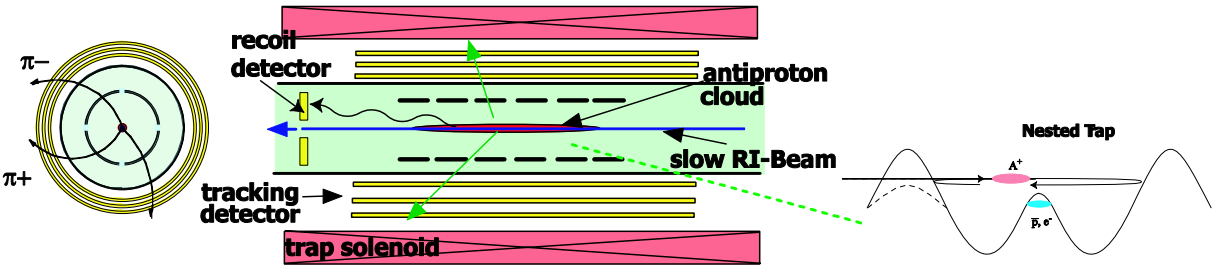


Figure 1: Nested trap and detector set-up for anti-protonic radioactive atom experiments. The set-up, with a space requirement of 10 x 10 m^2, will be located in the Low Energy Cave and requires a connecting beam line for the anti-protons from the NESR..

Collaboration

GSI, Germany
H. Geissel, W. Quint, C. Scheidenberger, M. Winkler

JYFL Jyväskylä, Finnland
J. Äystö, A. Jokinen, S. Kopecky, I. Moore, A. Nieminen

RIKEN Japan
M.Wada, Y. Yamazaki

Univ.Tokyo, Japan
E. Widmann

Univ. Warsaw, Poland
J. Jastrzebski ,W. Kurcewicz, A. Trzcinska

Convenor: Michiharu Wada (mw@riken.go.jp)
A. Trzcinska (agniecha@slcj.uw.edu.pl)
Deputy and **GSI contact person**: Wolfgang Quint (w.quint@gsi.de)

Corresponding author: Michiharu Wada (mw@riken.go.jp)

Table of contents

1. Introductory note

There are presently several ideas to produce and investigate antiprotonic exotic nuclei. These are described in the Letter of Intent for „A Facility for Low-energy Antiproton and Ion Research“ (FLAIR). The most prominent ones are the study of „Antiprotonic X-rays of heavy isotopes and nuclear structure“ and „Antiprotonic radioactive nuclides in traps“. Both aim at similar physics issues and are complementary to each other. Because of limited space, only one of them is described here without intending to assess or to set a priotity to either of them. For the experiments a connecting beamline FLAIR – Low-Energy Branch is needed.

2. Physics case

Different abundance of protons and neutrons at the surface of the nuclei is an important concern for nuclear structure study. Exotic properties of nuclei, such as halo and skin, have been investigated in nuclei far from the stability line [Tan85]. Antiprotonic atoms would be excellent probes for such different nucleon abundance at the surface, since annihilation of an antiproton dominantly occurs with a nucleon at the surface of a nucleus and the vanished nucleon can be identified by the total charge of the emitted pions or the residual nucleus. The future facility will provide both, slow antiprotons and simultaneously slow radioactive nuclei at the Low-Energy Branch. Using a beamline, which connects the Low-Energy Branch and the FLAIR area, this is a unique opportunity to create antiprotonic radioactive atoms of a wide variety of nuclides of all elements. The first candidates of target nuclides are

- In general the near drip-line nuclides in light mass region where very exotic properties have been already reported, in particular from refractory elements, which are not available elsewhere, and, more specific
- measurements in the vicinity of doubly-magic nuclei and along isotopic or isotonic chains such as $^{100...137}$Sn (Z=50) or ^{78}Ni... ^{100}Sn (N=50).

3 Proposed setup

Antiporotonic radioisotope (RI)-atoms are planed to be produced in a nested Penning trap as shown in Figure 1, where a cloud of antiprotons is trapped and slow RI ions are repeatedly bunch-injected [Wad03]. The antiproton capture cross sections of slow singly charged ions are theoretically estimated by Cohen [Coh03] and are as large as that of neutral atoms. A typical value is $1.3 * 10^{-15}$ cm^2 for $^{11}Li^+$ ions when the relative energy is 0.1 atomic units which corresponds to a $^{11}Li^+$ -beam energy of 33 eV in the antiproton rest frame. Assuming the number of trapped antiprotons is $5*10^6$ [Kur04] and that they are confined to 1 mm^2 , the target density is N(pbar) = $5*10^8$ cm^{-2} . Slow RI ions are bunch-injected in a nested trap and pass through the antiproton cloud for $5*10^5$ s^{-1} if the ions are 33 eV $^{11}Li^+$ and the trap length is 4 cm. Since we are mainly interested in very short-lived nuclei, we assume a short measurement cycle of 10 ms, in which only 10 RI-ions are involved when the RI-beam intensity is 10^3 s^{-1} . The production rate per cycle is then $Y= 1.3*10^{-15} * 5*10^8 * 10 * 5*10^3 = 3 * 10^{-2}$. Thus, in total 3 antiprotonic-$^{11}Li^{2+}$ ions can be produced per second.

Tracking detectors for charged pions and position-sensitive recoil ion detectors are planned to use. A captured antiproton annihilates with a nucleon and several pions and residual nucleus are emitted. Since pbar-n and pbar–p annihilations produce charged pions with a net charge of -1 and 0, respectively, a statistical comparison of the total number of detected π^+ and π^- directly provides the peripheral abundance of nucleons. The relative nucleon abundance ratio can be determined with 5% accuracy by $5 * 10^4$ annihilation events if the pion detection efficiency is 80% and the background event ratio is 10% [Wad03]. Furthermore, the cold residual nucleus becomes $^{A-1}_{N-1}Z$ and $^{A-1}_{N}(Z-1)$ from the parent nucleus $^{A}_{N}Z$, as consequences of pbar-n and pbar-p annihilations, respectively. Since the recoil ions

are fully stripped, the acceptance of recoil ion detectors is sufficiently large. We can deduce the mass, charge and momentum of the recoil nucleus from a measurement of the energy, time of flight which is triggered by the pion detectors, and detected position of recoil nucleus on the detectors.

Measurements of recoil ions coincident with pions allow to use a conventional vacuum system in which the trapping lifetime of an antiproton is very limited. It is because the dominant background molecules in UHV are hydrogen and an annihilation with a proton does not produce any recoil nuclei.

4 Feasibility

Trapping a large amount of antiprotons has been demonstrated at CERN AD by the ASACUSA group [Kur03]. They achieved the maximum stored number, $5*10^6$, using an RFQ-decelerator and a Penning trap with electron cooling. For the radioactive ions, there are no chemical processes in the entire scheme (in-flight separation, slowing down, stopping in and extraction from helium) and the only constraints are intensity and halflives larger than a few milliseconds. These experiments will become feasible if $>5 * 10^6$ antiprotons can be trapped in a pbar-RI formation trap and slow bunched RI-beams with an intensity of $>10^3\ s^{-1}$ are both provided simultaneously.

5 Implementation

5.1 Experimental Area

Width: 10m Length: 10m Height: 4m

In addition to the experimental setup itself, space for connecting beam line FLAIR – Low-Energy Branch is needed.

5.2 Radiation environment

No special requirements are needed.

5.3 Cost estimate

Antiprotonic atom formation trap incl. detectors:1.160 kEuro

5.4 Organization:

Commitment:
the Japanese partners will provide the RF ion guide system developed at RIKEN.

5.5 Time schedule:

For design, construction, and tests a period of 4 years seems appropriate.

5.6 Beam time

The setup will be permanently installed at the Low-Energy Branch. Experimental campaigns of about 4 weeks per year (overall, split in periods of typically one week each) should be envisaged and will be ideally combined with other experiments using same or similar nuclides from the ion catcher device.

This is feasible with fast or with slowly extracted beams from the SIS100/300. In addition, parallel operation with the antiproton program is necessary for the production of antiprotons

References

[Tan85] I.Tanihata,et al., Phys.Rev.Lett.55 (1985) 2676.
[Wad03] M.Wada and Y.Yamazaki, Nucl.Instr.and Meth.B 214 (2004) 196.
[Coh03] J.S.~Cohen, Phys.Rev.A 69 (2004) 022501.
[Kur04] Kuroda et al., to be published.

Letter of Intent

A universal setup for kinematical complete measurements of Reactions with Relativistic Radioactive Beams (R^3B)

The R^3B collaboration

14 April 2004

Abstract

A versatile reaction setup with unprecedented efficiency, acceptance, and resolution for kinematically complete measurements of reactions with high-energy radioactive beams is proposed. The setup will be located at the focal plane of the high-energy branch of the Super-FRS. The experimental configuration is based on a concept similar to the existing LAND reaction setup at GSI introducing substantial improvement with respect to resolution and an extended detection scheme, which comprises the additional detection of light (target-like) recoil particles and a high-resolution fragment spectrometer. The setup is adapted to the highest beam energies (corresponding to 20 Tm magnetic rigidity) provided by the Super-FRS capitalizing on the highest possible transmission of secondary beams. The experimental setup is suitable for a wide variety of scattering experiments, i.e., such as heavy-ion induced electromagnetic excitation, knockout and breakup reactions, or light-ion (in)elastic and quasi-free scattering in inverse kinematics, thus enabling a broad physics programme with rare-isotope beams to be performed.

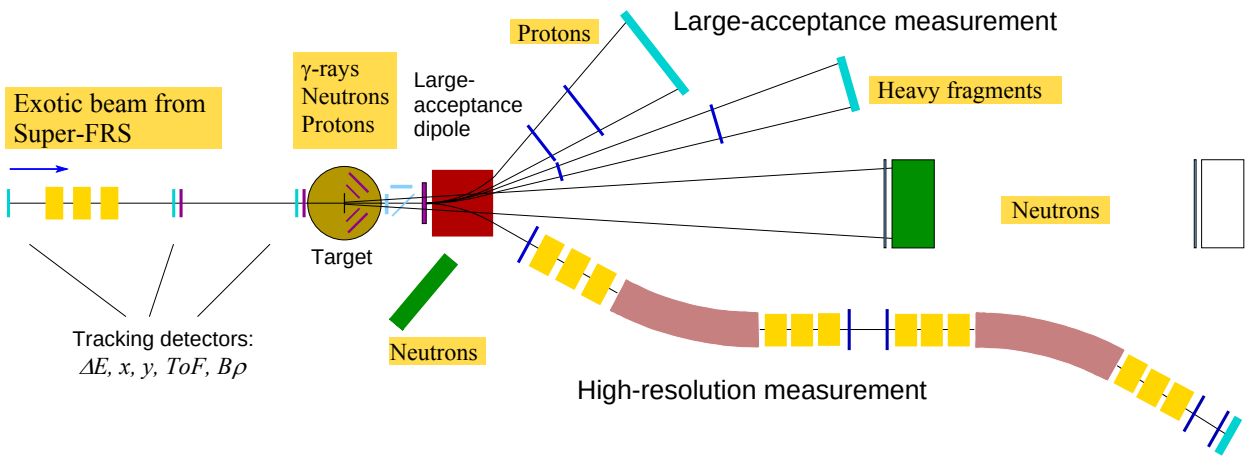


Figure 1: Schematic drawing of the experimental setup comprising γ-ray and target recoil detection, a large-acceptance dipole magnet, a high-resolution magnetic spectrometer, neutron and light-charged particle detectors, and a variety of heavy-ion detectors.

The R^3B Collaboration

Aarhus, Denmark, University of Aarhus
D.V. Fedorov, H.O.U. Fynbo, A.S. Jensen, K.-H. Langanke, K. Riisager

Argonne, USA, Argonne National Laboratory
J. Nolen

Bergen, Norway, University of Bergen
J.S. Vaagen

Birmingham, UK, University of Birmingham
M. Freer

Caen, France, GANIL
D. Boilley, C.E. Demonchy, W. Mittig, P. Roussel-Chomaz, H. Savajols

Daresbury, UK, CCLRC Daresbury Laboratory
R. Lemmon, J. Simpson, D. Warner

Darmstadt, Germany, Technische Universität
J. Enders, T. Nilsson, A. Richter, G. Schrieder

Darmstadt, Germany, GSI
T. Aumann, F. Becker, K. Boretzky, P. Egelhof, H. Emling, H. Feldmeier, H. Geissel, J. Gerl, M. Gorska, V. Henzl, J. Hoffmann, D. Henzlova, A. Kelic, I. Kojouharov, N. Kurz, G. Münzenberg, T. Neff, M.V. Ricciardi, T. Saito, K.-H. Schmidt, H. Simon, K. Sümmerer, W. Trautmann, S. Typel, H. Weick, O.Yordanov

Debrecen, Hungary, ATOMKI
A. Algora, M. Csatlós, Z. Gácsi, J. Gulyás, M. Hunyadi, A. Krasznahorkay

Dresden, Germany, Forschungszentrum Rossendorf
E. Grosse, A. Wagner

Dubna, Russia, Joint Institute for Nuclear Research
S.N. Ershov, L. Grigorenko

East Lansing, USA, NSCL, MSU
B. Sherrill

Gatchina, Russia, Petersburg Nuclear Physics Institute, PNPI
A. Khanzadeev

Giessen, Germany, Justus-Liebig-Universität
H. Lenske, M. Winkler

Gif sur Yvette, France, DAPNIA, CEA Saclay
N. Alamanos, A. Boudard, J.-E. Ducret, B. Gastineau, E. Le Gentil, V. Lapoux, S. Leray, S. Pietri, E. Pollacco, C. Volant

Göteborg, Sweden, Chalmers University of Technology
H. Johansson, B. Jonson, M. Meister, G. Nyman, M. Zhukov

Guildford, UK, University of Surrey
J. Al Khalili, W. Catford, W. Gelletly, R. Johnson, M. Oi, Z. Podolyak, P. Regan, P. Stevenson, I. Thompson, J. Tostevin, P. Walker

Heidelberg, Germany, Max-Planck-Institut
Heiko Scheit

Keele, UK, University of Keele
M. Bentley

Köln, Germany, Universität zu Köln
P. Reiter

Kolkata, Saha Institute of Nuclear Physics, India
U. Datta Pramanik

Krakow, Poland, Jagellonski University
P. Adrich, M. Kajetanowicz, A. Klimkiewicz, K. Korcyl, R. Kulessa

Krakow, IFJ PAN Krakow
A. Maj

Liverpool, UK, University of Liverpool
M. Chartier, P. Nolan

Lyon, IPN Lyon, France
Ch. Schmitt

Madrid, Spain, Instituto de Estructura de la Materia, CSIC
M.J.G. Borge, L.M. Fraile, E. Garrido, O. Tengblad

Mainz, Germany, Johannes Gutenberg Universität
O. Kiselev, J.V. Kratz

Manchester, UK, University of Manchester
D. Cullen, S. Freeman

Moscow, Russia, Kurchatov Institute
L. Chulkov, B. Danilin

Moscow, Russia, Institute for Nuclear Research, Russian Academy of Sciences
A. Botvina

Mumbai, India, Tata Institute of Fundamental Research
R. Palit

München, Germany, TU München
M. Böhmer, T. Faestermann, J. Friese, R. Gernhäuser, T. Kröll, R. Krücken

Obninsk, Russia, IPPE Obninsk
A. Ignatyuk

Orsay, France, IN2P3/IPN Orsay
Ch.-O. Bacri, Y. Blumenfeld, E. Khan, F. Rejmund, J.A. Scarpaci

Paisley, UK, University of Paisly
R. Chapman, M. Labiche, X. Liang, K. Spohr

Pyhäsalmi, Finland, CUPP project
T. Enqvist

RIKEN, Japan
R. Kanungo

Santiago de Compostela, Spain, Univers. of SdC
J. Benlliure, D. Cortina-Gil, I. Duran

Valencia, Spain, CSIC-University
B. Rubio, J.L. Tain

Yale University, USA
A. Heinz

York, UK, University of York
Ch. Barton

Spokesperson: T. Aumann E-Mail: t.aumann@gsi.de

Deputy: B. Jonson E-Mail: bjn@fy.chalmers.se

Contents

1. Introduction and overview

1.1. Experimental concept

During the past decade it has been demonstrated that reactions with high-energy secondary beams are an important tool to explore properties of nuclei far off stability, which allows detailed spectroscopic information to be extracted. The physics motivation for studying reactions with exotic nuclei is described extensively in various reports in the context of next-generation facilities, see, e.g., the 'Conceptual Design Report' (CDR) (http://www.gsi.de/GSI-Future/cdr) for the future FAIR project. High beam energies, in the range of a few hundred MeV/nucleon, allow a quantitative description of the reaction mechanisms [AlK03], while also having experimental merits, such as the possibility of using relatively thick targets (in the order of 1 g/cm^2). Moreover, due to the kinematical forward focusing full-acceptance measurements are feasible with moderately sized detectors. This makes it possible to gain nuclear-structure information from reaction studies even with very low beam intensities, as low as about 1 ion/s.

R^{3}B will cover experimental reaction studies with exotic nuclei far off stability, with emphasis on nuclear structure and dynamics. Astrophysical aspects and technical applications are also concerned. A survey of reaction types and associated physics goals that can be achieved is given in Table 1. A brief description follows subsequently in the next sub-section, for a more detailed discussion we refer to the CDR. In case of light-ion scattering, the experiments at R^{3}B are complementary to the ones proposed for the internal target in the NESR (see the LoI of the EXL collaboration). Here, the R^{3}B programme will focus on the most exotic short-lived nuclei, which cannot be stored and cooled efficiently, and on reactions with large-momentum transfer allowing the use of thick targets. The proposed experimental setup is adapted to the highest beam energies delivered by the Super-FRS, thus exploiting fully the highest possible transmission efficiency of secondary beams.

Table 1. Reaction types with high-energy beams measurable with R^{3}B and corresponding achievable information

Reaction type	*Physics goals*
Total-absorption measurements	Nuclear matter radii, halo and skin structures
Elastic p scattering	Nuclear matter densities, halo and skin structures
Knockout	Shell structure, valence-nucleon wave function, many-particle decay channels unbound states, nuclear resonances beyond the drip lines
Quasi-free scattering	Single-particle spectral functions, shell-occupation probabilities, nucleon-nucleon correlations, cluster structures
Heavy-ion induced electromagnetic excitation	Low-lying transition strength, single-particle structure, astrophysical S factor, soft coherent modes, low-lying resonances in the continuum, giant dipole (quadrupole) strength
Charge-exchange reactions	Gamow-Teller strength, soft excitation modes, spin-dipole resonance, neutron skin thickness
Fission	Shell structure, dynamical properties
Spallation	Reaction mechanism, astrophysics, applications: nuclear-waste transmutation, neutron spallation sources
Projectile fragmentation and multifragmentation	Equation-of-state, thermal instabilities, structural phenomena in excited nuclei, γ-spectroscopy of exotic nuclei

The proposed experimental scheme is based on that of the LAND apparatus which is used successfully in experiments with secondary beams from the FRS facility at GSI. The most essential upgrades concern the target recoil detector and the two magnetic spectrometers. A schematic view of the R^{3}B experimental setup is shown in Figure 1. The incoming secondary beams are tracked and identified on an event-by-event basis. Measurements of the magnetic rigidity $B\rho$ (position measurement at the dispersive focus in the Super-FRS), time-of flight ToF, and energy loss ΔE provide unique isotope identification and momentum determination. Although the secondary beam has a momentum spread of ±2.5%, the

momentum will be determined to an accuracy of 10^{-4} (event-wise). After the secondary target, the kinematically forward focused projectile residues are again identified and momentum analyzed.

Two modes of operation are foreseen depending on the demands of the experiments: i) A large-acceptance mode: Heavy fragments and light charged particles (i.e. protons) are deflected by a large-acceptance dipole and detected with full solid-angle acceptance, for most reactions envisaged (left bend in Figure 1). Resolutions for velocity and $B\rho$ measurements amount to about 10^{-3} allowing unique identification in mass and nuclear charge of also heavy fragments. ii) A high-resolution mode: here, the dipole magnet is operated in reversed mode, deflecting the fragments into a magnetic spectrometer (right bend in Figure 1). The envisaged resolution of 10^{-4} will allow, e.g., a precise measurement of the fragment recoil momentum in single-nucleon knockout and quasi-free scattering experiments even for heavy nuclei.

The large gap of the dipole provides a free cone of ±80 mrad for the neutrons, which are detected in forward direction by the large area neutron detector (new LAND). At beam energies around 500 MeV/nucleon, this corresponds to a 100% acceptance for neutrons with kinetic energies up to 5 MeV in the projectile rest frame. Depending on the requirements on resolution and acceptance, the detector with an active area of 2x2 m^2 is placed at a distance of 10 m to 35 m from the target.

The target is surrounded by a gamma-ray spectrometer. For most of the experiments envisaged, a high-efficiency total-absorption spectrometer (cooled CsI) is the optimum solution, which is also used to measure the energy of recoiling protons. For specific experiments requiring ultimate energy resolution for γ-detection, the Germanium spectrometer AGATA might be used alternatively. For elastic, inelastic and quasi-free scattering experiments or charge-exchange reactions, liquid hydrogen or frozen hydrogen targets are considered. Recoiling protons and neutrons are detected by a Si-strip array and plastic scintillators, respectively. For measurements at low momentum transfer, the use of an active target is foreseen. Fast neutrons stemming from (p,pn) type knockout processes can be measured by placing part of the LAND detector at angles around 45 degrees. The Si-strip array is also used as a high-granularity multiplicity detector array for measuring charged particles from the fire-ball, created in semi-peripheral collisions. The detector subsystems needed to achieve such a kinematical complete measurement of reactions with high efficiency and acceptance, which is of key importance for experiments with radioactive beams, are described in section 2 of this Letter of Intent.

1.2. Physics and reactions to be studied with R^3B

1.2.1. Total-absorption measurements

Nuclear *matter radii* may be inferred from total interaction cross sections derived from total-absorption measurements of radioactive ions in thick targets. This technique requires intensities of the order of only one ion/s. For instance, interesting results were obtained by a RIKEN-GSI collaboration [Suz95] by using beams of unstable sodium isotopes. These data, together with isotope-shift measurements, provide a first experimental manifestation of *neutron skins*. Beam intensities available at the new facility will allow systematic studies of this phenomenon in heavy nuclei. Such experiments can be performed using the high-resolution spectrometer after the dipole magnet.

1.2.2. Elastic proton scattering

The radial shape of the *nuclear density distribution* of exotic nuclei may be extracted from high-energy proton elastic scattering in inverse kinematics. Previous measurements [Ege02] using secondary beams at 700 MeV/nucleon have demonstrated the power of the method to investigate *halo* and *skin* structures in nuclei far off stability. Complementary to the experiments proposed at the storage ring, elastic scattering will be measured at R^3B using (thick) liquid hydrogen or frozen hydrogen targets, and focusing on larger momentum transfer and very short-lived nuclei, which are produced with low intensity only.

1.2.3. Knockout reactions

Break-up reactions induced by high-energy beams of exotic nuclei allow the exploration of *ground-state configurations* and of excited states. Due to limitations in beam intensity for heavier nuclei, this method has been restricted mainly to light *halo nuclei* so far. Knockout reactions have been used in particular to map the halo nucleon wave function in momentum space, from which their *spatial distribution* is derived via Fourier transformation [Sme99]. By γ-coincidence measurements, different single-particle configurations (including core-excited states) can be identified and corresponding *spectroscopic factors* may be obtained [Aum00]. The coincident measurements of neutrons allow the method to be utilized even if unbound states are involved. As an example, we mention the one-neutron knockout from the two-neutron halo nucleus ^{11}Li populating states in the unbound nucleus ^{10}Li, from which the occupancy of the $(s_{1/2})^2$ and $(p_{1/2})^2$ configurations of the two halo neutrons in the ^{11}Li ground state were deduced [Sim99].

At the new facility heavy neutron-rich nuclei, produced by in-flight fission can be studied. With high detection efficiency, secondary beam intensities in the order of ten ions/s are sufficient to extract detailed spectroscopic information, thus making nuclear structure studies possible even very far from stability. Key instruments will be efficient high-resolution γ-ray spectrometers, like the proposed cooled CsI array or AGATA in cases where the ultimate energy resolution is essential. In order to determine the angular momentum *l* of the knocked out nucleon, the momentum of the recoil fragment has to be measured with high precision. For medium-mass and heavy nuclei, the required relative momentum resolution is about 10^{-4}, which will be provided by the magnetic spectrometer behind the dipole magnet. Another promising field is the study of *resonant states in the continuum* [Mei02] or even *nuclei beyond the drip lines***,** see [Mei03] for a recent study of the unbound ^{5}H nucleus.

1.2.4. Quasi-free scattering

Knockout reactions using light targets, e.g., Be or C, have proven in the past to be very useful in gaining information on the wave function of the valence nucleons (see 1.2.3.). However, the strong absorption concentrates the reaction probability to the surface. Similar arguments hold for transfer reactions and Coulomb break-up reactions. Nucleon knockout reactions using protons, on the other side, allow one to determine the *spectral functions* of protons and neutrons in a wide range from the weakly bound valence nucleons to the deeply bound core states. Thus, in neutron rich nuclei one gains access to the hitherto unknown region of the strongly bound protons and simultaneously to the valence neutrons. Beside the *single-particle shell-structure, nucleon-nucleon correlations* may be investigated as well as *cluster* knockout reactions. For stable nuclei and in normal kinematics, (p,pN) reactions have been used in the past as spectroscopic tool [Kre95].

We intend to develop and apply the technique of quasi-free scattering using radioactive beams in inverse kinematics. At energies around 700 MeV/nucleon (which is high enough to ensure that the conditions for quasi-free scattering are met), both outgoing nucleons have energies in the range where the nucleon-nucleon cross section is at minimum, thus maximizing the transparency of the nucleus and minimizing final state interaction. Measurements such as (p,2p), (p,pn), (p,pd) etc. will become possible in a kinematically complete geometry, allowing a background-free measurement and also for a better control of final state interactions. To detect the proton recoils and other charged particles, we foresee two shells of Si microstrip detectors that surround the liquid hydrogen target integrated into a 4π gamma detector (CsI array). For (p,pn) reactions, part of the LAND neutron detector can be placed at angles around 45 degrees to detect the knocked-out neutrons with energies of few hundred MeV. The heavy fragment recoils are momentum analyzed utilizing the high-resolution spectrometer. Thus, the experiment determines the complete kinematics of quasi-free knockout reactions including those to continuum states (by measuring the invariant mass of the decaying system). Even reactions populating states *beyond the dripline* such as, e.g., ^{14}Be(p,p´p)^{13}Li, ^{14}Be(p,p´α)^{10}He, ^{11}Li(p,p´α)^{7}H, or ^{8}He(p,p´α)^{4}n, can be studied.

A thick liquid hydrogen target (200 mg/cm^2, ~3 cm thickness) will be used. The tracking of both protons and the beam will allow reconstruction of the interaction point with an accuracy much better than 3 mm, corresponding to an effective target thickness of less than 20 mg/cm^2. Thus, the relative momentum resolution of 10^{-4} for the fragment can be preserved. Experiments can be performed with intensities of 1000 ions/s corresponding to a luminosity of 10^{26} cm^{-2}s^{-1}.

1.2.5. Electromagnetic excitation

Electromagnetic processes in heavy-ion interactions at energies far above the Coulomb barrier give access to a wealth of nuclear structure information on exotic nuclei. At energies of the order of 1 GeV/nucleon, collective nuclear states at low and at high excitation energies are excited in peripheral heavy-ion collisions with large cross sections. Due to Lorentz contraction, the mutual electromagnetic field contains high frequencies up to several tens of MeV/ħ. *Surface vibrations* and particular *giant resonances* can be studied even with moderate beam intensities. The large cross sections allow experiments with minimum beam intensities of 1 to 1000 ions/s, provided efficient devices for γ-ray and particle detection are implemented.

Electromagnetic excitation of the *giant dipole resonance* induced by high-energy beams on targets of high nuclear charge was pioneered at GSI in exploring the multi-phonon states of the dipole resonance [Aum98]. This method was recently extended to secondary beams of exotic nuclei [Leis01]. It was shown that, e.g., for neutron-rich oxygen isotopes, *low-lying strength* appears and that the usual pattern of the dipole resonance strength distribution dissolves [Leis01]. With the proposed new facility, the measurement of the dipole strength of neutron-rich nuclei relevant for the *astrophysical r-process* will be feasible. In the region of the N=82 closed shell, for instance, the giant dipole strength can be deduced even beyond ^{132}Sn. For these heavier neutron-rich nuclei, the appearance of a new collective mode is predicted, the collective oscillation of valence neutrons (neutron skin) against the core, the so called *soft dipole mode*. The higher beam intensities also allow the study of giant quadrupole strength. Compared to dipole excitations, the required beam intensities are an order of magnitude larger. Giant resonance studies, in particular monopole and quadrupole excitations, will also be investigated at the NESR using the internal target and at the e-A collider (see the LoI's by the EXL and ELISe collaborations).

Besides resonant excitations, direct non-resonant transitions to the continuum occur for weakly bound nuclei. This 'threshold strength' is characteristic for the *single-particle structure,* being extremely sensitive to the spatial distribution of the valence nucleons. Similar to knockout, the l-value of the removed nucleon and spectroscopic factors can be deduced [Dat03]. For a halo-like structure, cross sections become very large, and spectroscopic information can be obtained with beam intensities down to 0.1 ions/s.

The continuum structure of drip line nuclei was studied so far only for very light nuclei. From a kinematically complete measurement of the decay not only the excitation spectrum, but also correlations can be studied as, e.g., in the three-body decay of Borromean halo nuclei like ^{11}Li or ^{6}He [Aum99,Ers01].

The experimental technique discussed here also allows the extraction of *(p,γ) and (n,γ) reaction rates*, which essentially determine the *astrophysical r-, and rp-reaction paths*. While the direct measurement of these rates is very difficult, the (γ,p) and (γ,n) reaction can be measured by electromagnetic excitation using high-energy secondary beams [Sch03] (see subsection 1.2.10).

1.2.6. Charge-exchange reactions

The (p,n) charge-exchange reaction can be used to excite *Gamow-Teller* (GT) and *spin-dipole* resonances by utilizing a liquid hydrogen target and measuring the slow neutrons with plastic scintillators surrounding the target. Studies of the GT strength are beside their importance in nuclear structure of particular astrophysical interest. Electron-capture reactions leading to *stellar collapse and supernova formation* are mediated by GT transitions. Basic understanding of all these processes requires reliable knowledge of the GT strength distribution in a large excitation energy range as well as in nuclei far off stability. Cross sections of the spin-dipole giant resonance excited in (p,n) reactions are rather directly related to the *neutron skin* thickness. Corresponding measurements were performed so far only for stable isotopes [Kra99]. With exotic nuclear beams, such measurements require secondary beam intensities of the order of 1000 ions/s, and thus a systematic study of neutron skins will be feasible by a method alternative to that consisting of a combination of proton and electron scattering data.

1.2.7. Fission

Since fission corresponds to a typical large-scale motion process, it has been recognised as one of the most promising tools for deducing information on *nuclear viscosity*, and on *shell effects* and *collective*

excitations at extreme deformation. This is not only important from the fundamental point of view but is of the prime interest in many challenging fields in nuclear physics, like e.g. *super-heavy element synthesis* or nuclide production in secondary-beam facilities. However, many questions still remain open, mainly due to the fact that experiments were restricted up to very recently to spontaneously fissioning isotopes and primordial or long-lived target nuclei. First-generation experiments performed at GSI have proven that the use of secondary beams indeed opens new prospects for studies of nuclear fission [Sch00]. More than 100 short-lived neutron-deficient nuclei will become available for such investigations. From the simultaneous measurement of proton and neutron number of both fission fragments in combination with their velocities, the fission dynamics may be studied in great details (e.g. influences of neutron and proton shells and of pairing correlation, temperature and deformation dependence of nuclear viscosity). The full isotopic distribution of the fission fragments is a sensitive signature of the excitation energy at which fission occurs in the statistical deexcitation cascade. The knowledge of the emitted neutrons and gamma radiation accompanying the fission process allows determining the excitation energies of the final products.

1.2.8. Spallation reactions

Spallation reactions are important in various fields of research such as *astrophysics, neutron sources* and *production of radioactive beams*. To get a quantitative understanding of the spallation mechanism and to improve its modeling, which is needed for accurate simulations of, e.g., sub-critical reactors coupled with high-intensity proton beams designed as *radioactive waste burners,* exclusive measurements of the reaction channels are mandatory. First experiments in this direction were performed [Duc03] at GSI at the ALADIN/LAND facility with high-energy (1 GeV/nucleon) Fe beams impinging on a liquid hydrogen target. Such studies are most interesting to be extended to heavier systems, which is prohibited at present, however, due to experimental limitations. We intend to measure spallation with two heavy beams, ^{208}Pb and ^{238}U. The first one constitutes the main component of the spallation target in accelerator driven systems, while the second allows studying the role of fission in spallation reactions. The R^{3}B facility provides the ideal setup for such studies making use of the large-acceptance dipole magnet with its large bending power. The goal will be to identify all the products in mass and nuclear charge (isotopic distributions) of the reactions and measure their velocities so that a complete reconstruction of the excited system at the end of the first stage of the reaction could be achieved. This would allow, for the first time for heavy projectiles, for a detailed study of the competition between the different de-excitation mechanisms (evaporation, fission, emission of intermediate-mass fragments, see also the sections on fission, projectile fragmentation).

1.2.9. Projectile fragmentation and multifragmentation

Heavy-ion collisions offer the possibility to probe nuclear matter under different conditions of densities and temperatures. In multifragmentation, nuclear matter at low densities and, more generally, modes of disintegration of dynamically unstable systems are probed. In particular, the expected link with the *nuclear liquid-gas phase transition* provides a continuing motivation for studying multifragmentation. In these reactions, systems of small and intermediate-mass nuclei surrounded by a nucleon gas may be produced, with properties close to what is expected in stellar processes as, e.g., supernova II explosions [Bot04]. Also properties of the high-density zones of the collision may be studied in the fragmentation of excited projectile spectators. The velocities of projectile residues are predicted to be sensitive to the non-local features of the nuclear mean field [Ric03].

Isotopic effects in multifragmentation, originating from the two-fluid nature of nuclear matter [Mue95], reflect the strength of the *symmetry term* in the *equation of state* whose density dependence is of importance for astrophysical applications. Experiments using the existing GSI facilities [Ala03] have shown that secondary beams of exotic nuclei are useful and necessary for obtaining systems with a sufficiently broad range of isotopic composition. With the new facility, this can be further extended, in particular to neutron-rich asymmetric matter for which the effects of the symmetry term are most strongly pronounced.

Projectile fragmentation of secondary beams in conjunction with *γ-ray spectroscopy* is a powerful method to explore *excited states in exotic nuclei.* This method is also addressed in the LEB LoI. The R^{3}B

setup is particularly well suited for cases at the very limits of the production rates, i.e., for the most exotic nuclei. Here, the better transmission using high-energy beams and the high efficiency of the CsI γ-array is advantageous.

1.2.10. Astrophysics

Reactions, which are of particular interest for astrophysics, were already mentioned in the previous sub-sections. These are Gamow-Teller transitions measured by charge-exchange reactions, spallation reactions, and Coulomb dissociation. The nuclei that will be accessible with the NUSTAR facility will allow exploring the reactions inverse to those relevant for the astrophysical rp- and r-processes by utilizing the electromagnetic excitation process at high beam energy. The cross sections for the direct capture reactions in the stellar environment are very small due to the stellar temperature (~20 keV) and the Coulomb barrier, while the cross sections for the inverse process, Coulomb dissociation, are much larger. Of special interest are the (γ,p) and (γ,n) cross section at very low fragment-nucleon relative energy. The proton tracking through the magnetic field of the large acceptance dipole will result in a momentum resolution of 10^{-3}. For the neutrons, a similar resolution is achievable by making use of a long time-of-flight path of ~35 m (ToF resolution <100 ps), resulting in an invariant-mass resolution of better than 20 keV (at 100 keV relative energy), thus making cross-section measurement feasible at energies relevant for astrophysics, down to about 10 keV. Here, the lead target thickness is limited to about 100 mg/cm^2 due to multiple scattering and energy loss. Still, with beam intensities of ~10^4 ions/s differential cross sections of 100 μb/(10 keV bin) can be measured within a few days.

2. Detector subsystems

2.1. Superconducting large-acceptance dipole

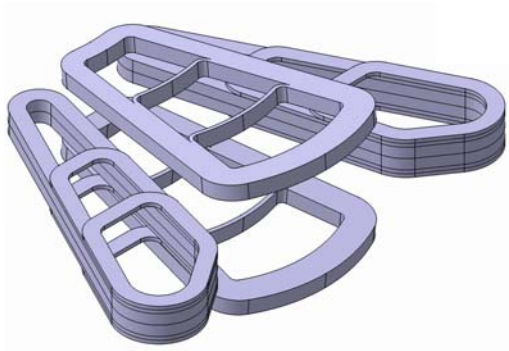


Figure 2: Layout of the four superconducting coils of the R^{3}B dipole. The side coils are optimized to reduce the fringe fields. The field integral amounts to about 5 Tm.

For the variety of experiments to be performed, a zero-degree superconducting dipole magnet was designed for the R^{3}B project. The main parameters of the spectrometer are: (i) A large vertical gap providing an angular acceptance of ±80 mrad for neutrons; (ii) A maximum bending angle of 40°, ensuring an acceptance close to 100% even for experiments with very different magnetic rigidities of the beam and the fragments; (iii) A high field integral of about 5 Tm, which allows a bending angle of 18° for a 15 Tm beam (e.g. 1 GeV/nucleon ^{132}Sn or 500 MeV/nucleon ^{8}He) or 14° for 20 Tm beams, the maximum rigidity provided by the Super-FRS. A momentum resolution of up to 10^{-3} can be achieved by tracking the particles with high resolution. The design includes four super-conducting coils, shown in Figure 2, which are tilted to match the required acceptance angle for the particles of interest. The side coils are optimized to reduce the fringe field, and guarantee a low magnetic field in the target region, where detectors have to be placed. A technical design report is available (http://www-land.gsi.de/r3b/docu/TDR-R3B-dipole.pdf). An application for funding the construction of the dipole has been submitted to the European Commission.

2.2 High-resolution spectrometer

A high-resolution magnetic spectrometer is foreseen for experiments demanding a precise momentum analysis after the target. This is particularly important for heavy beams (A>100), e.g., for quasi-free scattering and knockout reaction, where the momentum of the recoiling (A-1) fragments has to be analyzed in order to deduce the angular momentum of the knocked out particle from their momentum

distributions. A resolution of 20 to 50 MeV/c is required, corresponding to a relative momentum width $\Delta p/p \sim 10^{-4}$ for heavy beams. Other experiments with similar demands were discussed in the previous sections. For that purpose, the large-acceptance dipole will be operated in reversed mode deflecting the fragments into the magnetic spectrometer (see Figure 1). The possibility of deflecting the beam in both directions, allows keeping a permanent setup for both experiments ('large-acceptance' and 'high-resolution' mode). Possible spectrometer solutions will be investigated in the near future. As a starting point, the use of dipoles identical to the Super-FRS design is considered, thus reducing the costs. Since the acceptance of the Super-FRS (±2.5%) is large compared to the momentum transfer in the reaction, the emittance does not increase much (if only one reaction channel is considered), and it is sufficient to have the same acceptance before and after the target. In conjunction with fragment tracking, a resolution of $\Delta p/p \sim 10^{-4}$ seems to be achievable for momentum determination of the incident beams as well as for the outgoing fragments. Determining the momentum via tracking of the beam particles has the advantage compared to a dispersion matching scheme that the focus at the reaction target has not to be dispersive, thus avoiding a large beam spot at the target. Detailed calculations concerning acceptance and achievable resolution are in progress. The deflection of the fragments by the large-acceptance magnet into the spectrometer allows zero-degree operation (e.g. for knockout reactions or quasi-free scattering), but also enables measurements at larger angles by adjusting the magnetic field of the sweeper magnet.

2.3 Tracking detectors and velocity measurements

Various tracking detector systems with different demands are required. The incoming beam will be tracked (starting from the dispersive focus at the Super-FRS) in order to determine beam momentum, angle and position incident on the target, and, similarly, for the spectrometer after the target. In order to achieve the optimum momentum resolution, it is mandatory that the angular scattering induced by these tracking detectors being as small as possible. Silicon micro-strip, diamond strip, as well as position sensitive channel-plate detectors are considered. First prototype tests have already been started. For the large-acceptance mode, large-area detectors are placed behind the R^3B dipole magnet. For detection of light charged particles drift chambers with a size of about $1.2 \times 0.6 m^2$ including dedicated front-end electronics are presently being considered.

The velocity of the incoming beam as well as of the fragments has to be determined with a resolution of 10^{-3} in order to achieve unique isotope identification after the target also for heavy beams. Such a resolution is provided by a Cherenkov detector. The thickness of the Cherenkov radiator, however, represents a substantial target in the beam and further developments are needed in order to improve the situation significantly. For the large-acceptance mode, the flight path of the fragments amounts to about 10 m only, thus a time resolution for the ToF measurement of better than 40 ps is required. A time-of-flight wall consisting of fast scintillating material and ultra-fast phototubes is considered. First tests to explore the achievable time-resolution involving relatively large detector arrays ($\sim 1 m^2$) have been started. The very successful developments in resistive-plate chambers (RPC) might also provide an alternative solution.

2.4 Gamma detection

Total γ-absorption spectrometer

A 4π γ-calorimeter array surrounding the target with high efficiency and angular resolution is foreseen. At beam energies of typically 700 MeV/nucleon, the gamma energies are Lorentz boosted by a factor 2 to 3 in the forward directions at angles between 10 and 30 degree, where most of the intensity is located. Consequently, the photon detector should have a high absorption probability for photons with energies up to 10 MeV. Besides the γ-sum energy the detector has to provide γ-multiplicity and individual γ-energies for spectroscopy purposes. To obtain a proper γ-sum energy the strong angle dependent Doppler shift of individual γ-rays needs to be corrected for. Thus a granularity in the order of 1000 is required to maintain the intrinsic resolution of ≈2% obtainable with novel cost effective scintillation detectors. An "egg"-shaped array with asymmetric target position and increasing detector thickness at forward angles is anticipated. A sum energy efficiency of $\varepsilon_{sum} > 80\%$, a sum-energy resolution of $\sigma(E_{sum})/\langle E_{sum}\rangle$ below 10% and a multiplicity resolution of $\sigma(N_\gamma)/\langle N_\gamma\rangle$ better than 10% is

envisaged. The corresponding photo-peak efficiency is ε > 50% (at E_γ^{lab}=10 MeV) with a γ-energy resolution of 2%.

Design studies concerning possible and most economic solutions just started. One idea is to build an array consisting of cooled scintillators (e.g. undoped CsI or NaI). As alternative new inorganic scintillation materials like $LaBr_3$ need to be investigated. The light read-out of the scintillators will be performed by PIN diodes. The array will also be used for detecting and measuring the total energy of protons from quasi-free scattering in conjunction with a 2π array of light particle detectors.

High resolution γ-spectrometer

For high-resolution γ-spectrometry a forward wall of AGATA Ge tracking detectors (see LEB LOI) is foreseen. Employing half of the AGATA detectors in a compact arrangement covering the angular range from 9° to 45° at a target distance of 50 cm will result in a photo-peak efficiency of ε ≈ 12% (for E_γ.=1.3 MeV in the projectile rest frame). The corresponding energy resolution will be about 0.5% for a nucleus with a kinetic energy of 700 MeV/nucleon.

2.5 Proton recoil detector

In the quasi-free scattering (knockout) reaction, the knocked-out nucleon and the target (proton) recoil are scattered typically in a range between 20° and 70°, both having energies between 200 and 500 MeV (assuming beam energies around 700 MeV/nucleon). According to kinematical calculations, the detection setup for the recoil particles should consist of two layers of double sided Si micro-strip detectors, organized as barrels to cover the forward direction. The advantage of using such detectors is that very precise position and good energy loss information is provided. The first layer of the detector will be placed as close as possible to the target to improve the precision of vertex determination while minimizing the size (and the cost) of the first shell. The distance between the first and the second shell will be as small as possible, while compensating the lack of distance between the shells (for the tracking) by the high position resolution of the detectors (50 μm or better). 300 μm thick Si detectors for the second layer and 100 μm (or less to reduce multiple scattering) for the first layer, are considered. Chips with high dynamic range will allow also the detection of α-particles in case of using liquid helium target. The required angular resolution of 2 to 3 mrad is achievable with this type of detectors. The total energy of the recoils should be measured by the surrounding 4π sphere of scintillator (CsI, see 2.4), serving also to detect γ-rays. The detector will also be used as multiplicity detector (target hodoscope) for experiments dedicated to semi-peripheral collisions to obtain information on impact parameter and reaction plane.

Some of the reaction studies listed in Table 1 (i.e. elastic and inelastic scattering) require in special cases high resolution measurement of target-like reaction products at very low momentum transfer which is not possible with the standard target-detector setup. Such investigations are most favourably performed at the internal target of the NESR (see EXL LOI) for all cases where the lifetime of the exotic beam is sufficiently long (>500 ms) to allow for beam preparation in the CR/NESR rings. In contrast, for the case of very short-lived nuclei, the concept of an active target, where target and detector medium are identical, is considered. This detector concept has already been successfully applied for light exotic beams in experiments at GSI [Neu02] and GANIL [Dem03] and will be further developed for applications with heavy exotic beams by the ACTAR collaboration [ACTAR proposal to EURONS].

2.6 Low-energy neutron detector

In case of (p,n) charge-exchange reactions, the angle and energy of the low-energy neutron has to be detected from which the angular momentum transfer and the excitation energy is determined. In order to achieve the envisaged excitation-energy resolution of 1 MeV, an energy resolution of 10% and angular resolution of 1° for the neutron is required. This can be achieved by placing 4 cm thick plastic scintillators (30% efficiency) at a distance of about 1 m from the target (ToF resolution ~ 1 ns, flight time for a 5 MeV neutron is about 30 ns). Prototype tests are going on. The optimum geometry is presently being studied in Monte Carlo simulations.

2.7 High-resolution neutron time-of-flight spectrometer

The large-area neutron detector LAND is presently used to detect high-energy neutrons and determine their momenta via ToF and position measurement (obtained from a time difference measurement). The iron-converter/scintillator sandwich structure results in a rather high efficiency of more than 90% for neutron energies above 400 MeV. The obtained invariant-mass resolution is determined mainly by the time resolution of LAND. A better time resolution in the order of 100 ps is envisaged by using fast scintillating materials and ultra-fast phototubes for the NewLAND detector. Together with a long flight path of 35 m, high-resolution measurements will become possible. This in particular important for, e.g., the measurement of (γ,n) reactions relevant for astrophysics. Cross sections could be measured down to 10 keV fragment-neutron relative kinetic energy.

2.8 Multi-track ion detector for spallation and fission measurements

In order to detect multi-particle final states of spallation reactions or the two fragments in fission experiments, a multi-track detector has to be installed downstream of the R^3B dipole magnet. Two main goals have to be reached with this multi-track detector: i) The spectrometry of reaction fragments at the 10^{-3} level in momentum resolution in the laboratory frame; ii) The nuclear charge identification of these fragments from $Z = 1$ to $Z = 92$. Furthermore, this detector has to provide a detection efficiency very close to 100 % even for light fragments ($Z = 1$ or 2) n order to minimize efficiency corrections to measure cross-sections in a many-fold (multi-particle) final state phase space.

For light reaction products, such a detector will allow for the reconstruction of the kinematics at the reaction point in angle and momentum and thus for the kinematical reconstruction of the variables in the center of mass frame. For heavy fragments, fission products or projectile evaporation residues, the magnetic rigidity of the fragments with a resolution in mass of $A/\Delta A \sim 300$ (*FWHM*) has to be determined by combining the information with the measurements from the detectors upstream from the dipole. To achieve this, a spatial resolution of roughly 100 μm has to be aimed at in the detector design.

This detector will have to assure a multiple sampling measurement of trajectories. There are two reasons for this: i) To perform Z identification with ΔE measurements, the sampling of the primary energy loss signal has to be large enough (to be specified quantitatively, depending on the detector and its active material); ii) To avoid the huge combinatory of points, which has to be considered when working with partial information from planes of wires from MWPC's.

A gaseous detector such as a time projection chamber (TPC) is considered with vertical drift lines for the primary signals in order to assure the highest position resolution in the horizontal plane (the magnet dispersive plane) by center of gravity determination using the charges collected on the pads, and multi-hit readout with flash-ADCs in order to distinguish two trajectories on the top of each other in the detector. Further developments of the ALADIN MUSIC detector concept are also considered.

3. Trigger and data-acquisition system

Experiments with secondary beams at the Super-FRS require a determination of the projectile and fragment masses before and after the secondary reaction target, respectively. This involves measuring time of flight (ToF) and magnetic rigidity ($B\rho$). Since ($B\rho$) of an ion can only be determined at a dispersive focal plane of the Super-FRS, the corresponding position measurements are performed at rather large distances from each other. Likewise, the detectors for detecting neutrons, charged particles, or decay radiation are located far from each other. The R^3B data acquisition concept, therefore, foresees distributed subsystems that acquire data (position, time, energy loss, decay radiation etc.) in self-triggered mode synchronized by time stamps; sub-events are sent to the event builder via fast optical links. These subsystems will be designed along the same lines as the present RISING distributed readout. It is also very likely that developments underway at other experiments (e.g. within the EU project I3HP with their more ambitious requirements) will provide solutions for front-end preprocessors, high-speed data links, or time-stamp distribution that can be adapted to the needs of R^3B, thereby making use of synergetic effects.

Following current trends, we foresee largely digital electronics based on ultra-fast sampling of the direct or preamplifier signals, followed by digital signal processing rather than analog pulse shaping or time

pick-off. These concepts have been successfully applied at the present FRS for measuring atomic masses in the ESR via the ToF method, and are indispensable for the readout of future γ-ray tracking detectors like AGATA. Whereas at present such approaches rely largely on expensive commercial modules with small numbers of channels, efforts will concentrate on designing custom-built inexpensive modules that allow digitizing economically the few thousand channels foreseen in R^3B. A common data-acquisition system for the NUSTAR experiments is aimed for.

4. Physics performance

To a large extend, the proposed setup bases on further developments of the existing LAND reaction setup at GSI. The concept and design of the experimental setup addressed in this LoI, and the corresponding estimates on resolution and performance are based on the expertise that has been gained from experiments and developments at the present facility. The existing setup will be extremely instrumental in designing and testing detector prototypes. Several of the developments discussed above will be implemented already for experiments using radioactive beams in Cave C. Ion-optical calculations for the design of the magnetic spectrometer are on the way, which are the basis for simulations exploring the limits in achievable momentum resolution implying tracking through the spectrometer. Such studies will also define the demands on detector design concerning thickness and resolution. The designs of the proton-recoil detector as well as the total-absorption gamma spectrometer will be based on GEANT simulations as well as on tests of prototype detectors and electronics. The final conceptual and technical design together with the simulation results will be presented in technical design reports to be worked out by the collaboration.

5. Implementation

5.1 Experimental area and radiation environment

The R^3B experiment will be located at the focal plane of the high-energy branch of the Super-FRS. An experimental hall of about 50 m length and 20 m wide is required (depending on the final design of the magnetic spectrometer) with standard technical infrastructure including crane and cooling system for the super-conducting magnets. Access has to be provided to bring in large and heavy equipment. The height of the beam line should be at least 2.0 meter. Typical beam intensities used for R^3B experiments will range between few ions/s up to 10^7 ions/s. All beams up to uranium have to be considered. The cave should be accessible independent of operation of other Super-FRS beam lines, e.g., the ring branch and the low-energy branch.

5.2 Cost estimates

The costs for the planned R^3B setup are dominated by the investments needed for the large-acceptance dipole (5.7 MEuro) and the high-resolution magnetic spectrometer, see Table 2. Only a preliminary and rough cost estimate can be given since the designs for many detectors and the high-resolution spectrometer are not finalized. For the magnetic spectrometer, the costs for two Super-FRS dipole stages were assumed (~8 MEuro). An application was submitted to the European Commission for funding of the construction of the large-acceptance dipole within the 6th framework programme. If the proposal will be accepted, construction costs of 5.0 MEuro will be funded by the EU.

Table 2. Preliminary cost estimate

Task	Cost estimate (MEuro)
Quadrupole triplet in front of the target	1.0
Super-conducting large-acceptance dipole magnet	5.7
High-resolution magnetic spectrometer	8.0
Total-absorption gamma spectrometer	2.0
High-resolution time-of-flight neutron detector	2.2
Heavy-ion and charge particle detectors incl. readout electronics	0.8
Total	19.7

5.3 Organisation and responsibilities

The research teams forming the R^3B collaboration have a large experience with regard to the scientific and technological aspects addressed in this LoI and will participate according to their expertise and physics interest. Table 3 gives an overview on the tasks and a tentative list of institutes involved in the working groups in charge for the individual developments. Names of responsible persons are given for each institute; those having a coordinating role for the specific sub-task are indicated with *italics*. A coordination board (CB) will be formed out of representatives of the participating groups taking over major duties in developments. The role of this board will be to ensure overall monitoring of the quality and progress of the developments. The CB will consist of about 10 members including the spokespersons of the collaboration.

Table 3. List of tasks and tentatively assigned working groups and responsibilities

Task	Group
Spokespersons	T. Aumann, B. Jonson
Large-acceptance dipole	CEA Saclay (J.E. Ducret, *B. Gastineau*), GSI (T. Aumann)
High-resolution spectrometer	Argonne (J. Nolen), Giessen (*M. Winkler*), GSI (T. Aumann), MSU (B. Sherrill), UK (R. Lemmon)
Tracking detectors ToF measurements	CEA Saclay (A. Boudard, J.E. Ducret), FZ Rossendorf (A. Wagner), GSI (T. Aumann, A. Kelic, *K. Sümmerer*), St. Petersburg (A. Khanzadeev), TU München (R. Gernhäuser, *R. Krücken*) Santiago (*J. Benlliure*), CEA Saclay (E. Pollacco), GSI (K. Sümmerer) Krakow (R. Kulessa)
Total-absorption gamma spectrometer	GSI (*J. Gerl*), MPI Heidelberg (H. Scheit), Uni Köln (P. Reiter), TU München (R. Krücken), UK (K. Spohr), Valencia (B. Rubio), Kolkata (U. Datta Pramanik)
Proton recoil detector	CEA Saclay (*E. Pollacco*), Chalmers (B. Jonson), Uni Mainz (*O. Kisselev*), GSI (P. Egelhof, H. Emling), Kurchatov (L. Chulkov), GANIL (W. Mittig), TU Darmstadt (T. Nilsson), UK (*R. Lemmon*)
Low-energy neutron detector	Debrecen (*A. Krasznahorkay*), GSI (H. Emling)
Neutron ToF spectrometer	GSI (*H. Emling*), Krakow (R. Kulessa), Santiago (J. Benlliure)
Multi-track ion detector	CEA Saclay (*J.E. Ducret*), GSI (K.-H. Schmitt), IPN Orsay (Ch.O. Bacri)
DAQ	GSI (H. Simon), Krakow (R. Kulessa), TU München (M. Böhmer), UK (I. Lazarus)
Simulations	Aarhus (K. Riisager), Chalmers (B. Jonson), Orsay (Ch.O. Bacri), Madrid (M .Borge), Santiago (*D. Cortina*), Valencia (J.L. Tain), UK (M. Labiche)
(UK collaboration: Uni Keele, Uni Surrey, Uni Liverpool, Uni Manchester, Uni Birmingham, CCLRC Daresbury, Uni York, Uni Paisley)	

Synergies with other LoI's

Several detector developments and in particular the readout electronic and data acquisition systems are to a large extent similar to those discussed, e.g., for the experiments using internal targets in the storage ring (see EXL LoI) and the electron scattering experiment at the e-A collider (see ELISe LoI). Of course, such synergetic effects have to be exploited. A close collaboration among the participants of R^3B, EXL and ELISe is therefore desired.

5.4 Time schedule

According to the time plan for the construction of the Super-FRS, the high-energy beam line will be the first operational, starting commissioning in 2011. Consequently, the experimental setup will be moved to the new experimental area in 2010, and first experiments may be expected to start in 2011. Most of the detector developments are intended to be ready already for first experiments to be performed in Cave C using the current FRS. The high-resolution magnetic spectrometer will be built and installed in the new hall in parallel with the construction of the Super-FRS.

Table 4. Time schedule for implementation of the R^3B experiment

	2003	2004	2005	2006	2007	2008	2009	2010	2011
Large-acceptance dipole									
High.resolution spectrometer									
Tracking detectors									
proton arm									
large-area ion and ToF det.									
Super-FRS and spectrometer									
Total-absorption γ-detector									
Proton-recoil detector									
Low-energy neutron detector									
Neutron ToF detector									
Move setup into new Cave									

	Simulations, R&D, design		Prototyping, construction
	Installation, tests		Commissioning, experiments

5.5 Beam time considerations

Typical experiments to be performed at R^3B need two to three weeks of beam time. A total requirement of 3 months/year beam on target is estimated. The experiment requires DC or DC like beams. In most cases, secondary beams will be used, which will be produced and separated with the Super-FRS. Most experiments will ask for the maximum reachable intensity with energies up to 1500 MeV/nucleon. This means that SIS100 as well as SIS300 (as stretcher ring) will be needed. The use of the Super-FRS implies that no other experiments with radioactive beams, e.g., low-energy branch or ring branch, can be operated in parallel. Parallel operation with other programmes is possible to some extent, which will, however, reduce the duty cycle implying longer runs in consequence.

References

[Ala03] K. Kezzar *et al.*, (ALADIN-FRS-LAND collaborations), SIS experiment S254.
[AlK03] J. Al-Khalili and F. Nunes, J. Phys. G 29 (2003) R89.
[Aum98] T. Aumann, P.F. Bortignon, H. Emling, Annu. Rev. Nucl. Part. Sci. 48 (1998) 351.
[Aum99] T. Aumann *et al*., Phys. Rev. C 59 (1999) 1252.
[Aum00] T. Aumann *et al*., Phys. Rev. Lett. 84 (2000) 35.
[Bot04] A.S. Botvina and I.N. Mishustin, Phys. Lett. B 584 (2004) 233.
[Dat03] U. Datta Pramanik *et al*., Phys. Lett. B 551 (2003) 63.
[Dem03] C.E. Demonchy, PHD-thesis, Univ. of Caen (2003), Ganil T 03 06.
[Duc03] J.E. Ducret *et al*., SPALADIN experiment, performed at GSI, proposal S248.
[Ege02] P. Egelhof *et al*., Eur. Phys. J. A 15 (2002) 27.
[Ers01] S.N.Ershov, B.V.Danilin and J.S.Vaagen, Phys. Rev. C 64 (2001) 064609.
[Kra99] A. Kraznahorkay *et al*., Phys. Rev. Lett. 82 (1999) 3216.
[Kre95] G. Krein, Th.A.J. Maris, B.B. Rodrigues, E.A. Veit, Phys. Rev. C 51 (1995) 2646.
[Lei01] A. Leistenschneider *et al*., Phys. Rev. Lett 86 (2001) 5442.
[Mei02] M. Meister *et al*., Phys Rev. Lett. 88 (2002) 102501.
[Mei03] M. Meister *et al*. Phys. Rev. Lett. 91 (2003) 162504.
[Mue95] H. Müller and B.D. Serot, Phys. Rev. C 52 (1995) 2072.
[Neu02] S.R. Neumeier, Nucl. Phys. A 712 (2002) 247.
[Ric03] M.V. Ricciardi *et al.*, Phys. Rev. Lett. 90 (2003) 212302
[Sch00] K.-H. Schmidt *et al*., Nucl. Phys. A 665 (2000) 221.
[Sch03] F. Schümann *et al*., Phys. Rev. Lett. 90 (2003) 232501.
[Sme99] M.H. Smedberg *et al*., Phys. Lett. B 452 (1999) 1.
[Sim99] H. Simon et al., Phys. Rev. Lett. 83 (1999) 496.
[Suz95] T. Suzuki *et al.*, Phys. Rev. Lett. 75 (1995) 3241.

Rare-Isotope-Beam Experiments at the CR-RESR-NESR Storage Rings:

April 8, 2004

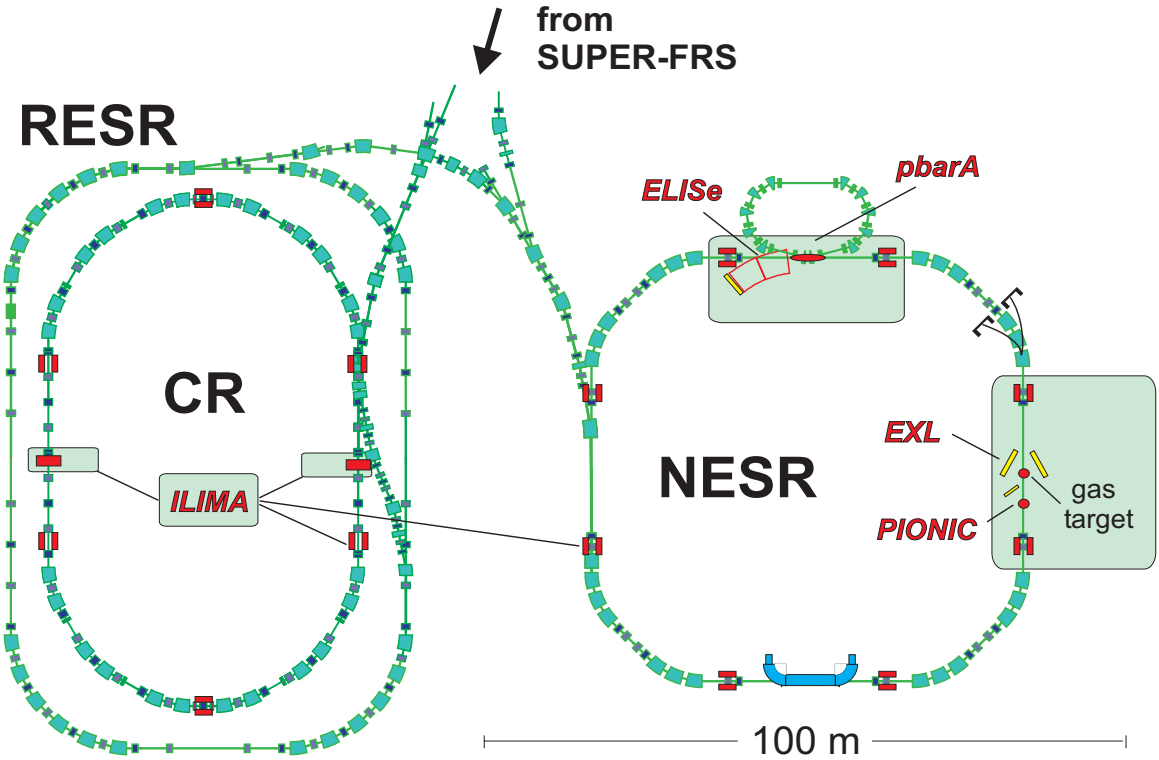
I. **Study of Isomeric Beams, Lifetimes and Masses (ILIMA)**

II. **Exotic nuclei studied in light-ion induced reactions at the NESR storage ring (EXL)**

III. **Electron–Ion scattering in a Storage Ring (eA collider) (ELISe)**

IV. **Antiproton-Ion Collider : A tool for the measurement of neutron and proton rms radii of stable and radioactive nuclei (pbarA)**

V. **Spectroscopy of Pionic Atoms with Unstable Nuclei (PIONIC)**



Executive summary

This section comprises Letters of Intent proposing experiments with stored beams of unstable nuclei at the international Facility for Antiproton and Ion Research (FAIR). The experiments rely on the CR-NESR storage-ring system, meanwhile extended by adding a third RESR ring, and the electron-ion (eA) collider as described in the Conceptual Design Report (2001) for this facility. One of the Letters of Intent suggests an additional option of stored antiprotons colliding with ion beams.

The **ILIMA** collaboration proposes precision measurements of nuclear masses and lifetimes of stored exotic nuclei and studies with isomeric beams, to be performed at the CR and NESR. The experiments extend the successful experimental program at the existing ESR storage ring to nuclei near and at the drip lines, out of reach at present facilities.

The **EXL** collaboration proposes to explore specific nuclear structure aspects of unstable nuclei in intermediate-energy light-ion induced reaction studies at the internal NESR target. This conceptually new scheme benefits from accumulation and fast cooling of secondary beams in the CR-RESR-NESR storage ring complex and from a planned detector system for exclusive-type experiments.

The **ELISe** collaboration proposes electron scattering experiments, which allow for the first time studying ground state and transition form factors of unstable nuclei with a pure electromagnetic probe. Experiments of exclusive type are performed at the eA collider, i.e., an electron storage ring intersecting the NESR, using newly developed electron and ion spectrometers.

The eA collider may as well be used to facilitate collision experiments between stored ion and **antiproton beams** as proposed by another collaboration; antiprotons of 30 MeV kinetic energy are to be stored in the electron ring. Measurements of total and partial antiproton absorption cross sections deliver the rms radii of neutron and proton ground state densities in stable and radioactive nuclei and nucleon momentum distributions.

Spectroscopy of **pionic atoms** with unstable nuclei by using the (d, ^{3}He) nuclear reaction is proposed in another Letter of Intent. The experiment is intended to be performed at the NESR facility with stored secondary beams of 250 MeV per nucleon using a dedicated setup.

As indicated within the storage-ring Letters of Intent, there is, in part, overlap with regard to the physics case being addressed. On the experimental side, some of the instruments or data acquisition have similar development lines. As expressed in the respective LoI subsections, cooperation is already discussed in order to benefit from synergetic efforts.

Letter of Intent

I. Study of Isomeric Beams, Lifetimes and Masses (ILIMA)

ILIMA Collaboration

April 2004

Abstract

Precision measurements of nuclear masses and lifetimes of stored exotic nuclei at relativistic energies and studies with isomeric beams are proposed. The planned experiments are triggered by the successful experimental program at the present FRS-ESR facilities. The new Super-FRS-CR-NESR facility will yield access to interesting nuclei near and at the driplines which can not be accessed with the present facilities.

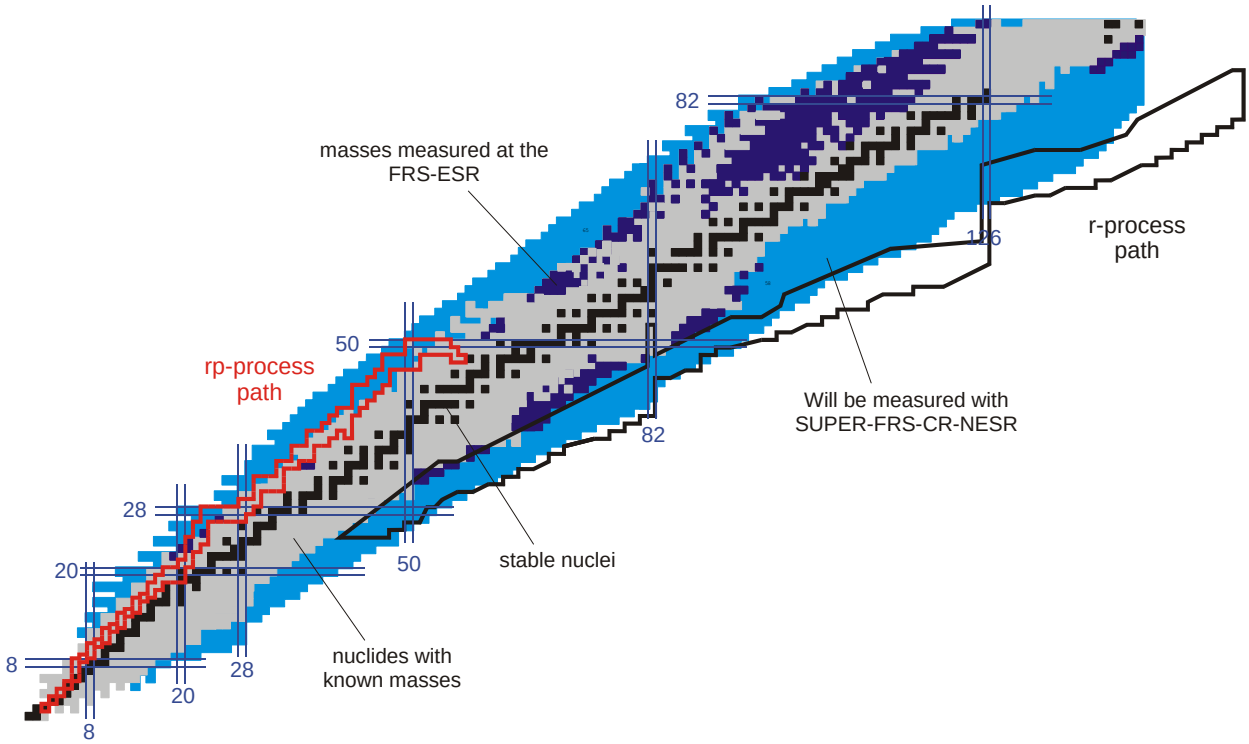


Figure 1. The chart of nuclides with known and unknown masses. The range of the mass measurements performed presently in the storage ring ESR at GSI is marked as a dark-blue area. Nuclides with still unknown masses which will become accessible with the new facilities, the SUPER-FRS, the double-storage ring system of CR and NESR, are indicated by the light-blue area. Astrophysical r- and rp-processes are indicated as well.

List of the ILIMA Collaboration

GSI Darmstadt, D-64291 Darmstadt, Germany
K. Beckert, P. Beller, F. Bosch, D. Boutin, A. Dolinski, B. Franczak, B. Franzke, J. Gerl, H. Geissel, F. Herfurth, E. Kaza, H.-J. Kluge, C. Kozhuharov, Yu.A. Litvinov, M. Matos, G. Münzenberg, F. Nolden, W. Quint, C. Scheidenberger, M. Steck, Th. Stöhlker, K. Sümmerer, S. Typel, H. Weick, M. Winkler.

Michigan State University, East Lansing, Mi 48824, USA
M. Portillo, H. Schatz.

Technische Universität München, D-85748 Garching, Germany
T. Faestermann, P. Kienle, L. Maier, P. Ring, D. Vretenar.

St. Petersburg Nuclear Physics Institute, 188350 Gatchina, Russia and St. Petersburg State University, 198904 St. Petersburg, Russia
S.A. Litvinov, Yu. N. Novikov, G. Vorobiev.

Justus-Liebig Universität Gießen, D-35390 Gießen, Germany
Z. Di, T. Dickel, A. Fettouhi, R. K. Knöbel, M. Petrick, W. R. Plaß.

University of Surrey, Guildford, GU2 5XH, UK
Z. Podolyak, P.M. Walker.

Los Alamos National Laboratory, Los Alamos, NM 87545, USA
Th. Buervenich, M. Hausmann, D. Madland, D. Vieira.

Johannes Gutenberg Universität Mainz, 55099 Mainz, Germany
K.-L. Kratz, B. Pfeiffer, A. Ostrowski.

University of Manchester, Manchester, M13 9PL, UK
D. Cullen.

Niigata University, 950-2181 Niigata, Japan
T. Ohtsubo.

CSNSM-IN2P3-CNRS, F-91405 Orsay, France
G. Audi, D. Lunney.

Saitama University, Sakura-ku, 338-8570 Saitama, Japan
T. Suzuki, T. Yamaguchi.

Aristotle University, GR-54124 Thessaloniki, Greece
G.A. Lalazissis.

Tsukuba University, 305-8577 Tsukuba, Japan
A. Ozawa.

Soltan Institute for Nuclear Studies, 00681 Warsaw, Poland
Z. Patyk.

University of York, Heslington, York, YO10 5DD, UK
C. Barton, D. Jenkins, R. Wadsworth.

Spokesperson: Yu.N. Novikov, St. Petersburg Nuclear Physics Institute, Russia
Deputy: Yu.A. Litvinov, GSI Darmstadt, Germany

Table of contents

1 Physics case

1.1 Research objectives

Nuclear masses and lifetimes of exotic nuclei in ground and isomeric states are basic quantities which are essential for the understanding of nuclear structure and the creation of the elements in stars.

Nuclear masses are of fundamental interest, because they reflect the complex interaction of the nucleons and the forces acting among them in the nuclear medium. From systematic precision measurements, i. e., the variation of neutron (proton) number along isotopic (isotonic) chains, important information can be derived, like location of driplines, the development of shell closures, the changes in shapes and pairing. Such investigations are indispensable for testing the predictive power of nuclear models and refining their theoretical foundations. Today the challenge is to measure the masses and lifetimes of exotic nuclei up to the limits of nuclear stability. New experimental developments involving storage rings yield access to measurements of bare and few-electron ions in the laboratory, thus under conditions that prevail in hot stellar environments.

A great research potential is that not only ground state properties can be studied but also those of isomeric states, which are populated in projectile fragmentation and fission reactions at relativistic energies. Isomers with long half-lives usually result from specific structural features, related to angular momentum quantum numbers or shape degrees of freedom. These features may themselves result from the breaking of several nucleon pairs. In a general sense, the study of multi-quasiparticle isomers gives an opportunity to quantify the characteristics of the pair field. The experimental possibilities will dramatically expand with the availability of isomeric beams that can be used for secondary nuclear reactions, which will open novel ways to explore the nuclear landscape. A great novelty is the possibility of neutron radioactivity from high energy isomers in very neutron-rich nuclei. Furthermore, so-far unknown, long-lived isomers close to the drip-lines can alter astrophysical pathways. Due to their range of half-lives, isomers also offer special access, through their decay, to otherwise inaccessible states. The ability to store isomers and separate them from their ground states, hence to measure their half-lives and excitation energies, and thereafter to measure their reaction modes and decay modes, has wide implications for future nuclear structure investigations.

The proposed investigations at the new facility will focus on:

- mapping of large areas of the unknown mass surface:
  - near and at the driplines, investigate pairing among loosely bound nucleons;
  - $N \approx Z$ nuclei, investigate the role of the neutron-proton pairing and to test a restoration of SU(4) symmetry in heavy nuclides;
  - in the region of shell closures, e.g. around doubly magic nuclides ^{48}Ni, ^{78}Ni, ^{100}Sn;
  - along specific chains of isotopes and isotones, explore predicted shell quenching away from stability;
  - at the pathways of nucleosynthesis in stars (r- and rp-process), in particular waiting points;
- lifetimes of highly-charged ions, their decay modes and branching ratios;
- mass-resolved isomeric states and related nuclear properties;
- the production of and investigations with pure isomeric beams.

1.2 Experimental concept

Mass measurements of exotic nuclei are a challenge because of the low production cross sections and the inherent large emittance and longitudinal momentum spread of the radioactive ion beam. A further difficulty arises from the fact that the most interesting nuclei near the drip lines are short-lived and thus limit the preparation and observation times.

Two methods have been developed at GSI for accurate mass measurements of stored exotic nuclei at relativistic energies: *'Schottky Mass Spectrometry (SMS)'* for cooled beams of longer-lived isotopes [1], and *'Isochronous Mass Spectrometry (IMS)'* for hot beams of short-lived fragments [2]. Both methods, well established in previous experiments, are based on precise measurements of the revolution frequency which unambiguously characterizes the mass-to-charge ratio of the circulating ions.

In the SMS the velocity spread of the relativistic hot fragment beams is reduced by electron cooling. For IMS the ring optics is tuned to an isochronous mode such that the different velocities are exactly compensated by different trajectories.

These two experimental methods are especially well-suited to measure effectively a large part of the mass surface in one run. In this way the systematic errors can be kept small if the reference masses for the calibration are reliable. The corresponding mass measurements in the Penning trap system of the Low-Energy Branch of the Super-FRS will yield complementary results and are predestinated to provide very accurate new reference masses. The Penning trap experiments will have the highest accuracy for the longer-lived nuclei and the isochronous method in the storage ring will yield access to very short-lived isotopes down to microsecond range.

The lifetimes of stored nuclei can be obtained with two independent methods. The first one is to measure directly the intensity changes of the stored ion beams. The second is based on the fact that daughter and mother nuclides differ by their mass-to-charge ratio. Then the resulting daughter nuclei can be recorded with particle detectors placed near the orbit of mother nuclides. Both methods yield redundant information by simultaneous measurement of the decay of mother and the population of daughter nuclides.

Nuclei in isomeric states were already observed throughout the campaign for mass and life-time measurements with the present FRS-ESR [3,4] facility due to superb resolution obtained with stored cooled beams. Using the Bρ-ΔE-Bρ separation method, isotopic pure beams can be injected and stored in the rings. Depending on the half-life and excitation energy of isomeric states a pure isomeric beam can be prepared.

1.3 Competitiveness

The unique opportunity of the FAIR facility is the combination of the in-flight separator SUPER-FRS and a system of storage rings CR-RESR-NESR. The SUPER-FRS will be an ideal tool to provide short-lived nuclides of all elements for precise mass and half-life measurements in the new storage rings. Unique investigations of decay modes and half-lives of stored bare and highly charged nuclides are possible. Another unique feature of the new facility will be to give access to pure isomeric beams.

The present status of the knowledge of atomic masses [5] and the large area of hitherto unknown masses, which will become accessible with the new facility, is illustrated in Figure 1. The light blue area covers those nuclides where direct mass measurements will be possible with the FAIR facility. The lifetimes will be measured simultaneously with mass measurements. Most of these nuclides can only be investigated with the new facility.

2 Experimental techniques

2.1 Experimental setup

The combination of the Collector Ring (CR) and the New Experimental Storage Ring (NESR) is designed for fragment beams and will accept the full phase space of the secondary beams delivered by the SUPER-FRS. The efficient storage of fission fragments will give access in particular to exotic neutron-rich nuclei. The goals for the mass resolving power and accuracy are about 10^6 and 20–50 keV, respectively. We have already achieved these values for SMS in previous experiments, whereas for IMS still some improvements are required.

Experiments involving nuclei with very short half-lives, less than 0.5 s down to the μs range, will be performed in the CR operated in the isochronous mode. In addition to conventional diagnostic detectors, the experimental equipment in the CR will include time-of-flight detectors and very sensitive resonant Schottky probes, both enable precise revolution frequency measurements in a very short time. An independent measurement of the lifetimes will be performed by measuring the daughter nucleus in particle-identification detectors placed near the closed orbit of the stored beam.

An important feature of the new ring system is the short cooling time of about 1 s for all fragment species an ideal condition for SMS in the NESR. These cooling times will be a factor of 5 shorter than for the current ESR. The task of the CR is the efficient collection and fast precooling of secondary beams to a relative momentum spread of 10^{-4} and an emittance of $\varepsilon = 1\ \pi$ mm mrad before the exotic nuclei are

transferred to the NESR. This high beam quality is achieved by bunch rotation and subsequent stochastic cooling within 500 ms, for a typical fragment beam characterized by an initial momentum spread of ±1.75%. The fact that the beam has been precooled in the CR will considerably reduce the time for electron cooling in the NESR. With this precooling it will be possible to reduce the emittance by electron cooling to $\varepsilon < 0.1\ \pi$ mm mrad with a relative momentum spread of $\Delta p/p < 10^{-4}$ for an intensity of 10^8 fully stripped uranium ions within another 100 ms. These parameters are an upper limit and considerably lower values for the emittance and momentum spread will be achieved for lower intensities. The mass and half-life measurements will be performed using Schottky probes. The experimental setup is schematically illustrated in Figure 2.

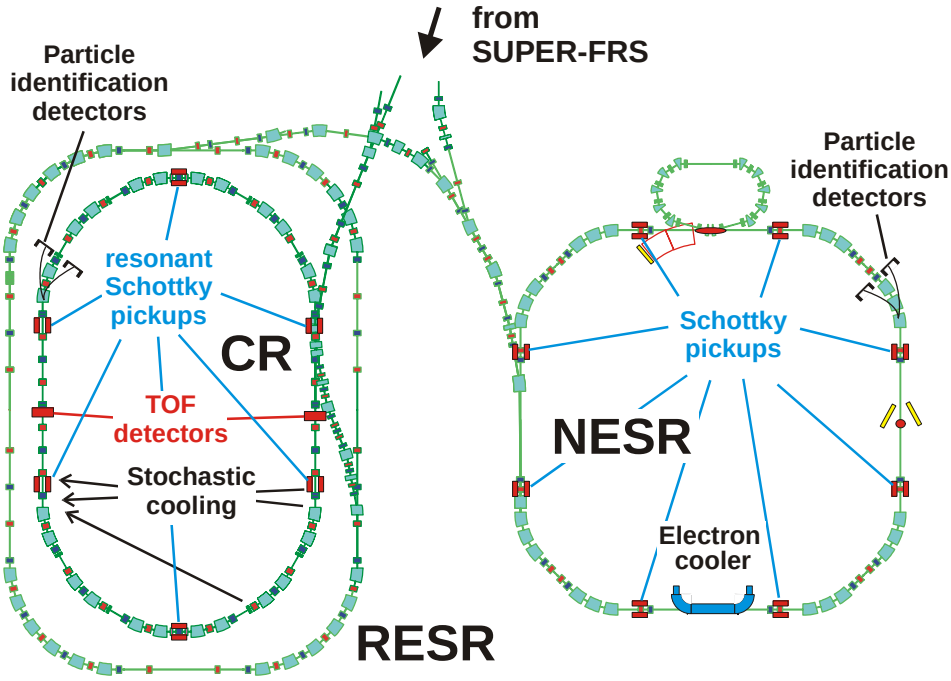


Figure 2. The storage ring facilities for direct mass and half-life measurements and studies with isomeric beams. Exotic nuclei separated with the Super-FRS will be injected into the Collector Ring CR. Mass and half-life measurements of very short-lived nuclides (down to few tens µs) will be performed in the CR operated in isochronous mode. Longer-lived nuclides (longer than 1 s) will be stochastically precooled in the CR and be transferred via RESR to the NESR. Here, they will be further cooled by electron cooling and Schottky Mass Spectrometry will be applied. Movable particle-identification detectors for the independent half-life measurements will be installed after one of the dipole magnets in the CR and NESR.

2.2 Mass and life-time measurements in the NESR

The measurements in the NESR will be performed with well-cooled beams ($\Delta v/v < 10^{-6}$). The cooling time limits the access to nuclei with lifetimes larger than 1 s. The revolution frequencies of all ion species stored simultaneously are obtained nondestructively by a Fourier transformation of the correlated signals which they induce in pick-up probes at each turn.

An example of SMS is illustrated in Figure 3 with a part of a typical Schottky frequency spectrum of cooled bismuth fragments at 370 MeV/u. Isotopes with previously known and unknown masses are marked in the spectrum by the blue and red labels, respectively. The high kinetic energy of the projectile fragments stored into the ESR allows to measure the masses in bare, H-like, and He-like charge states, a feature which yields redundancy in particle identification, calibration, and mass measurement. An illustration of the mass resolution achieved and of the ultimate sensitivity down to single ions is presented in the inset. The mass peaks of one ion each of the ground and isomeric states of ^{143}Sm ions are clearly resolved. A resolving power of 7.5×10^5 was achieved and masses of more than 500 nuclides were measured with a typical accuracy of 30 keV in one experiment. The achieved ultimate sensitivity down to single stored ions will allow mass measurements of extremely exotic nuclides with very low production cross-sections.

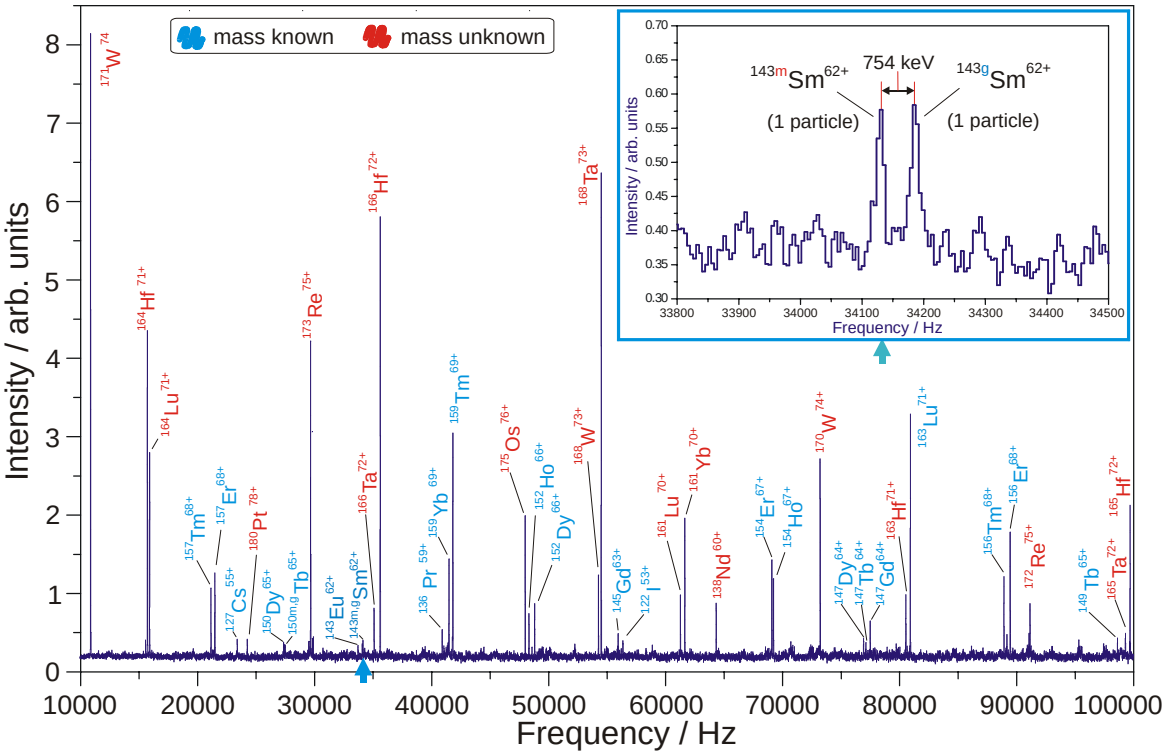


Figure 3. Typical frequency spectrum of cooled bismuth fragments from the FRS injected into the ESR at 370 MeV/u. The inset shows a frequency spectrum obtained from only two bare ^{143}Sm ions, one in the ground state, ^{143g}Sm, the other one in the isomeric state, ^{143m}Sm.

The area of the Schottky frequency peak is proportional to the number of stored particles and their charge squared. This allows a simultaneous determination of half-lives by measuring the change of the areas. The power of the method is demonstrated in Figure 4 where sequential Schottky spectra are plotted. In the left part of the figure each partial spectrum was recorded for one second. In the first two seconds stochastic precooling was used followed by electron cooling. The decaying of the isomeric state of $^{207}Tl^{81+}$ ions ($T_{1/2}$ = 1.5 s) and the growing intensity of the $^{207}Pb^{81+}$ ions, the daughter nuclides of the bound β-decay of $^{207}Tl^{81+}$, can be clearly seen. In this experiment the branching ratio of the continuum β-decay and bound β-decay of fully ionized $^{207}Tl^{81+}$ atoms was measured for the first time. In the right panel of Figure 4 the decay of the ground state of $^{207}Tl^{81+}$ ions to the lead ions is shown over several minutes.

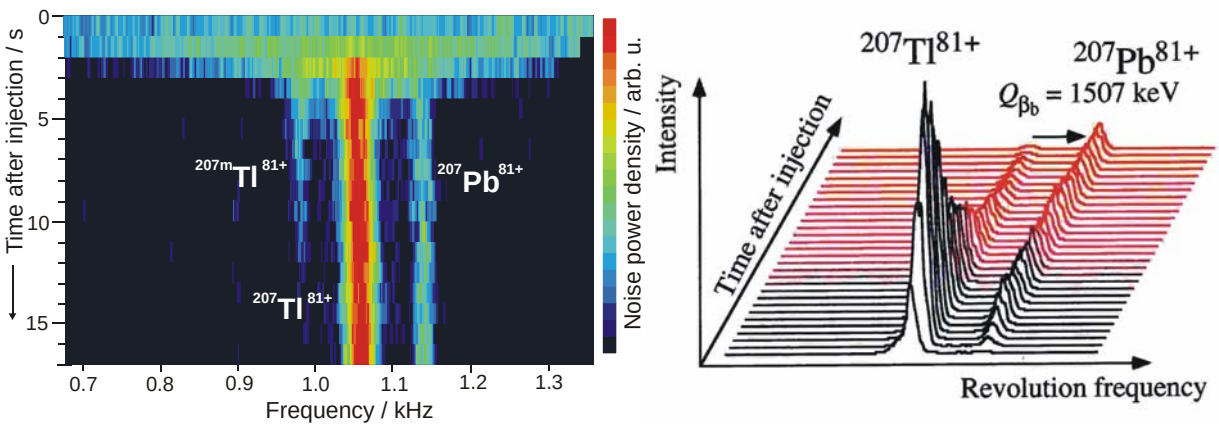


Figure 4: Sequential frequency spectra of stored $^{207}Tl^{81+}$ and $^{207}Pb^{81+}$ ions. In the left panel, the decay of an isomeric state of $^{207}Tl^{81+}$ ions and population of bound state beta daughter $^{207}Pb^{81+}$ are clearly seen. In the right panel, the decay of the ground state of $^{207}Tl^{81+}$ ions to the lead ions is shown over several minutes.

In order to increase the sensitivity and efficiency of this technique it is proposed to use several Schottky pick-ups in a correlated mode.

2.3 Mass and life-time measurements in the CR

Exotic nuclei with half-lives shorter than the cooling time are investigated by the IMS. A special mode of the CR is required, characterized by the property that the revolution frequency only depends on the mass over charge ratio of the isotope and is independent of the velocity of each individual ion. Thus, precise mass measurements can be performed without applying cooling. The revolution frequency is measured either by highly sensitive Schottky probes or by a time-of-flight (TOF) detector mounted in the storage ring aperture.

The prototype of the TOF detector is installed in the present ESR and has been successfully applied in recent mass measurements with uncooled short-lived krypton fragments and with uranium fission fragments. As in the SMS, nuclides of known and unknown masses are included in the revolution frequency spectra. A mass resolving power of 1.5×10^5 and an accuracy of 100 keV were obtained in first runs. Both characteristics can be improved with several position-sensitive TOF detectors and new pick-up probes.

In the isochronous mode, lifetimes from about 10 µs to about 1 ms can be measured with the time-of-flight detector and longer-lived nuclei with nondestructive pickup probes.

2.4 Production and study of pure isomeric beams

The combination of the SUPER-FRS with storage rings will provide access to pure isomeric beams. Already with the present FRS the Bρ-ΔE-Bρ separation method provides monoisotopic beams in the storage ring ESR as illustrated in Figure 5. In the left panel of this figure a Schottky spectrum is shown when the FRS is operated as a pure magnetic-rigidity analyzer. Applying the energy-loss separation with shaped degraders leads to a pure monoisotopic beam of ^{52}Mn circulating in the ESR (right panel).

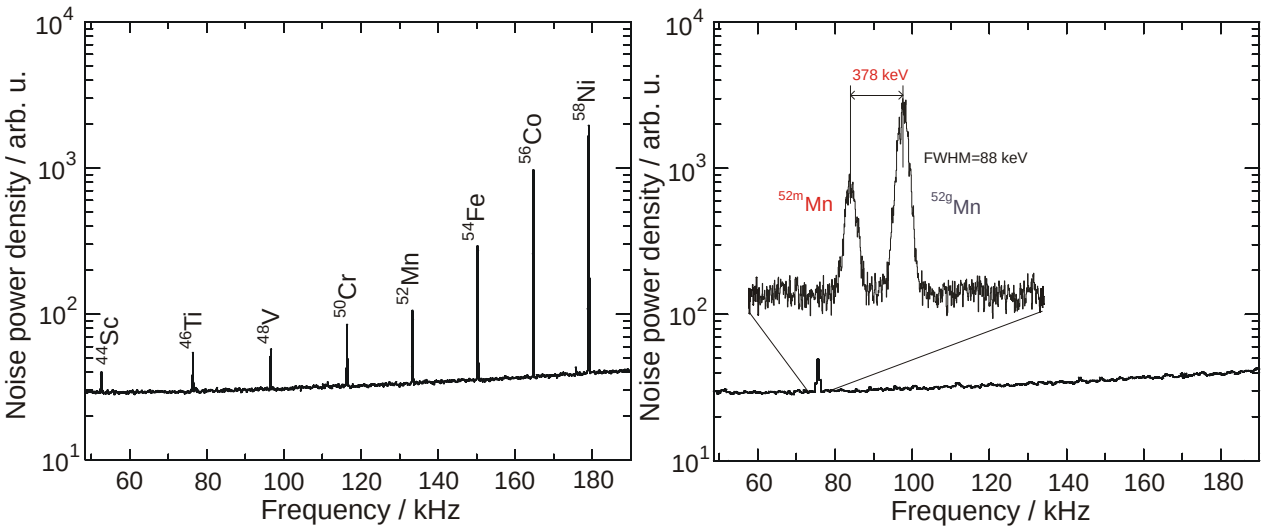


Figure 5: Schottly spectra of stored fragments in the ESR. Left panel, the FRS is used as a magnetic-rigidity analyzer resulting in an isotope-cocktail beam in the storage ring whereas the Bρ-ΔE-Bρ separation method provides monoisotopic beams as demonstrated for ^{52}Mn ions. The stored ^{52}Mn ions consists of nuclei in the ground and isomeric states which are resolved by SMS, see zoomed part in the right panel.

When a monoisotopic beam consisting of ions in the ground and isomeric states is stored and cooled in the ring, depending on the excitation energy it is possible to resolve the states as demonstrated by the mass-resolved ground and isomeric states of ^{52}Mn ions in Figure 5. In this case the excitation energy of the isomeric state is merely 378 keV.

Two ways are proposed to remove the ions in the ground state. First, one can use the mechanical scrapers installed inside the ring aperture to remove the ground state. This can be achieved either by moving the scrapers or by moving the beam. The latter can be done with a small change in velocity by the electron

cooling force or by the use of selected RF excitation. This method is fast and the access to the pure isomeric beams can be achieved within a few seconds. Secondly, if the half-life of the isomeric state is significantly longer than the half-life of the corresponding ground state and, if it decays mainly via beta channel, then the purification is easy to achieve by storing the beam till the ground state decays completely.

2.5 Detector summary and data acquisition systems

The application of the three types of detectors for direct mass and lifetimes measurements in the NESR and CR rings is summarized in Table 1. For the studies with pure isomeric beams the detectors built for the in-ring reaction and scattering studies (see EXL LOI) will be used in addition to the equipment listed.

Table 1. Detectors needed for measurements of masses and lifetimes in the CR and NESR.

Detector	CR		NESR	
	masses	lifetimes	masses	lifetimes
time-of-flight	X	X		
Schottky pick-up	X	X	X	X
particle detector		X		X

The data acquisition systems for Schottky pick-ups in the CR and NESR can be designed based on the present experience. It must provide fast sampling of the raw data and store them online. It is important to record the measured frequencies without disturbing noise and background. Presently the sampling is achieved with 640 kHz 16bit ADC, which corresponds to 1.28 MB of raw data per second. About 100 GB of disk space is needed for one day of experiment per Schottky probe. This data acquisition and storage has been successfully applied in previous FRS-ESR experiments.

The data stream from the TOF detector is presently collected by a commercial digital oscilloscope (Tektronix TDS 7404) which has an analog bandwidth of 4 GHz, sampling rate of 20 GSamples/s (8 bit) and allows for a continuous measurement of up to about 2 ms. The data storage was done with a raid system. Future developments will certainly allow a higher data rate and more storage depth. It is obvious that all new detector developments can be performed and tested with the present FRS-ESR facilities.

3 Implementation

3.1 Organization and responsibilities

The ILIMA collaboration consists of scientists from 15 institutions of 8 countries. Main tasks for the implementation of the proposed program are listed in Table 2.

Table 2. Tasks and responsibilities.

Task	Group	Contact
Key experiments: - mass measurements - life-time measurements - isomeric beams	NPI St. Petersburg GSI JLU Giessen MSU JGU Mainz TU München Uni. Surrey CSNSM Orsay	Yu.N. Novikov Yu.A. Litvinov W. Plaß H. Schatz K.-L. Kratz T. Faestermann, P. Kienle P.M. Walker D. Lunney
Coupling of the Super-FRS with the CR and NESR	GSI	H. Weick, M. Winkler, A. Dolinski, P. Beller
Stochastic cooling in CR	GSI	F. Nolden
Electron cooling in NESR	GSI	M. Steck
Time-Of-Flight detectors	JLU Giessen	W. Plaß
Particle identification detectors	TU München	T. Faestermann
Resonant Schottky pick-ups	GSI JLU Giessen	C. Kozhuharov, Yu.A. Litvinov, F.Nolden W. Plaß
Software development	GSI	Yu.A. Litvinov

	NPI St. Petersburg SINS Warsaw Uni. Saitama Uni. Niigata	Yu.N. Novikov Z. Patyk T. Yamaguchi T. Ohtsubo
DAQ systems for Schottky pick-ups and data storage	GSI	C. Kozhuharov, Yu.A. Litvinov
DAQ systems for TOF detectors and data storage	JLU Giessen GSI	W. Plaß C. Kozhuharov, M. Matos
Theory: - Interpretation of data - New predictions - Improvement of theoretical models	GSI LANL SINS Warsaw NPI St. Petersburg TU Munich Uni. Thessaloniki	F. Bosch, S.Typel Th. Buervenich, D. Madland Z. Patyk Yu.N. Novikov P. Ring, D. Vretenar G.A. Lalazissis
Mass evaluation	CSNSM Orsay	G. Audi

3.2 Time schedule

The detectors will be designed and assembled before the building of the new storage rings. They will be tested in the existing ESR. The detectors are small in size and will be mounted inside the new rings during their construction on appropriate positions according to the ion-optical design and performance of the rings.

The measurements with short-lived nuclides will be possible with the IMS directly after the commissioning of the CR and the Super-FRS. With increasing projectile intensity, we will stepwise proceed towards the driplines. After commissioning of the RESR and NESR with primary beams we can start the full program.

Task/Milestone	Period	Cost estimate / k€
Adjustment of the ion-optical parameters of the CR for the isochronous mode	2004	
R&D of Schottky pick-ups in CR	2005-2006	500
R&D of Schottky pick-ups in NESR	2005-2006	300
Further development and construction of the time-of-flight detectors	2004-2006	200
R&D particle identification detectors	2004-2006	200
Technical Report	end of 2004	
Technical Design Report	end of 2005	
Software development	2004-2008	
Data acquisition systems for SMS	2004-2008	500

Total: 1700 k€

3.3 Beam time considerations

The proposed experiments will require the Super-FRS, CR, RESR and NESR facilities. For experiments on mass and half-life measurements in the CR, we can accept beam pulses each few hundred milliseconds. These experiments can partially be done in parallel with an independent program in the NESR.

Experiments in the NESR will require beam to be delivered every few seconds, every few minutes or even every few hours dependent on the task.

References

[1] T. Radon et al., Phys. Rev. Lett. **78** (1997) 4701; Nucl. Phys. **A677** (2000) 75.
[2] M. Hausmann et al., Nucl. Instr. and Meth. **A446** (2000) 569.
[3] H. Geissel et al., Nucl. Instr. and Meth. **B70**, 247 (1992).
[4] B. Franzke, Nucl. Instr. and Meth. **B24/25**, 18 (1987).
[5] G. Audi, O. Bersillon, J. Blachot, A.H. Wapstra, Nucl. Phys. **A729** (2003) 3.

Letter of Intent for

Exotic nuclei studied in light-ion induced reactions at the NESR storage ring

EXL Collaboration

April 08, 2004

Abstract

We propose to study the structure of unstable exotic nuclei in light-ion scattering experiments at intermediate energies. The EXL objective is to capitalize on light-ion reactions in inverse kinematics by using novel storage-ring techniques and a universal detector system providing high resolution and large solid angle coverage in kinematically complete measurements. The apparatus is foreseen being installed at the internal target at the NESR storage-cooler ring of the international Facility for Antiproton and Ion Research (FAIR).

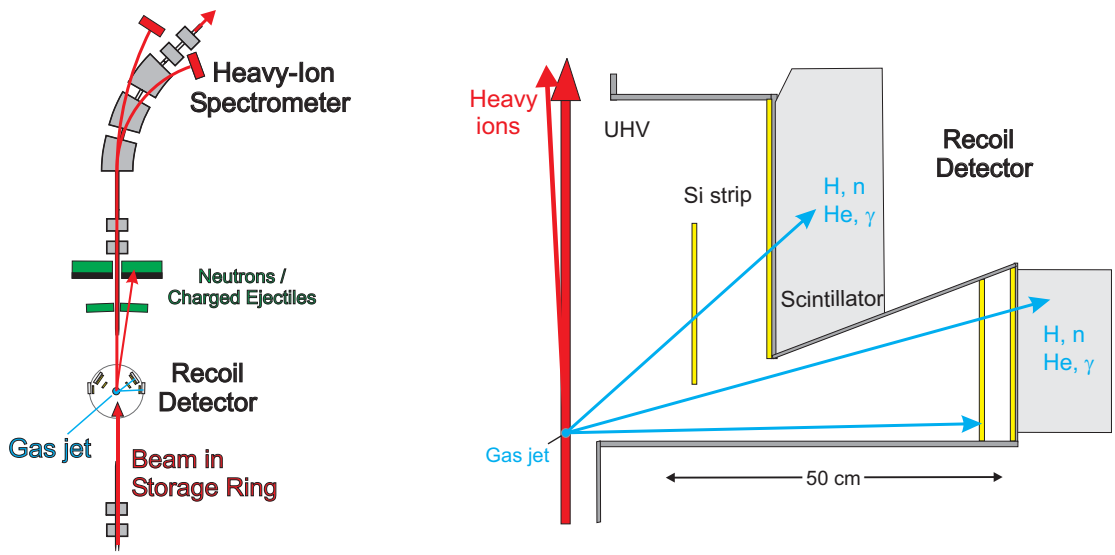


Fig. 1: Schematic view (cross section) of the EXL detector system.
Left: Setup built into the NESR storage ring. Right: target-recoil detector.

Table of Contents:

The EXL Collaboration

Universität Basel, Switzerland (UNIBAS)
K. Henken, J. Jourdan, B. Krusche, T. Rauscher, D. Rohe, F. Thielemann

Birmingham University, United Kingdom. (U.K.)
M. Freer

Daresbury Laboratory, United Kingdom (U.K.)
R. Lemmon

Technische Universität Darmstadt, Germany (TUD)
T. Nilsson, G. Schrieder

Gesellschaft für Schwerionenforschung, Darmstadt, Germany (GSI)
T. Aumann, F. Becker, K. Beckert, P. Beller, K. Boretzky, A. Dolinski, P. Egelhof, H.Emling, H. Feldmeier, B. Franczak, H. Geissel, C. Kozhuharov, Y. Litvinov, T. Neff, F. Nolden, C. Peschke, H. Simon, M. Steck, T. Stöhlker, K.Sümmerer, S. Typel, H. Weick, M. Winkler

Institute of Nuclear Research, Debrecen, Hungary (ATOMKI)
A. Algora, M. Csátlos, Z. Gáski, J. Gulyás, M. Hunyadi, A. Krasznahorkay

Joint Institute of Nuclear Research, Dubna, Russia (Dubna)
A.G. Artukh, Yu.M. Sereda, S.A. Klygin, Yu.G. Teterev, A.N. Vorontzov, A.E. Korchagin, S.V. Polovnikov

Institut für Kernphysik, Forschungszentrum Jülich, Germany (FZ J)
D. Protic, D. Grzonka, F. Rathmann

University of Liverpool, United Kingdom (U.K.)
M. Chartier

Lund University, Sweden (Lund)
V. Avdeichikov, L. Carlén, P. Gobulev, B. Jakobsson

Instituto de Estructura de la Materia (CSIC), Madrid, Spain (Madrid)
E. Moya de Guerra, M.J.G. Borge, L. Fraile

Universidad Complutense, Madrid, Spain (Madrid)
J.M. Udias Moinelo

Johannes Gutenberg Universität, Mainz, Germany (Mainz)
O. Kiselev, J.V. Kratz

Universitá da Milano and INFN, Italy (Milano)
A.Bracco, PF. Bortignon, G. Coló

Russian Research Centre, Kurchatov Institute, Moscow, Russia (Kurchatov)
L. Chulkov

Technische Universität München, Germany (TUM)
M. Böhmer, T. Faestermann, R. Gernhäuser, L. Maier, R. Krücken, P. Kienle, K. Suzuki

Institute de Physique Nucleaire, Orsay, France (IPN)
E. Khan, J.A. Scarpaci

Department of Physics, Osaka University, Osaka, Japan (Osaka)
Y. Fujita

Riken, Hirosawa, Saitama, Japan (RIKEN)
R. Kanungo

CEA Saclay, France (CEA)
N. Alamanos, F. Auger, A. Drouart, A. Gillibert, V. Lapoux, L. Nalpas, E. Pollacco, C.Simenel

St. Petersburg Nuclear Physics Institute, Gatchina, and St. Petersburg State University, Russia (Gatchina)
V. Ivanov, A. Khanzadeev, E. Rostchin, O. Tarasenkova

University of Surrey, Guildford, United Kingdom (U.K.)
J. Al-Khalili, W. Catford, R. Johnson, P. Stevenson

The Svedberg Laboratory, Uppsala, Sweden (TSL)
C. Ekström, L. Westerberg

University of York, Heslington, United Kingdom (U.K.)
C. Barton, B. Fulton, D. Jenkins, A. Laird

Contact:	H. Emling	Email: h.emling@gsi.de
	M. Chartier	Email: mc@ns.ph.liv.ac.uk
	E.C. Pollaco	Email: lolly@hep.saclay.cea.fr
GSI liaison:	P. Egelhof	Email: p.egelhof@gsi.de
	H. Weick	Email: h.weick@gsi.de

1. Physics case

1.1 Research objectives

Light-hadron scattering has provided a wealth of nuclear structure information for stable nuclei. Usually, such reactions are performed in 'normal kinematics', i.e., where intermediate-energy light ions are scattered from a fixed target consisting of stable nuclei. Secondary beams of exotic nuclei produced by in-flight fragmentation of primary heavy ion beams can be scattered from stable light target nuclei using the so-called 'inverse kinematics'. Because of luminosity constraints and the specific circumstances of inverse kinematics, these scattering experiments could not be applied to a similar extent as the normal scattering experiments. Up to present, such investigations are restricted to light exotic nuclei and only with limited applications even there. A wide and unique discovery potential would emerge if such reactions can be studied using exotic nuclei far from the valley of stability.

Using inverse kinematics on light stable target nuclei, essential contributions can be made to most important nuclear structure and nuclear astrophysics issues discussed in the context of exotic nuclei, in particular for neutron-rich nuclei, towards which the current thrust is being directed. Here, we just name a few interesting topics:

- The unusual matter distributions in neutron-rich nuclei near the neutron drip line, exhibiting neutron halos and skins;
- the shell structure in nuclei of extreme proton-to-neutron asymmetry leading to a disappearance of the known magic numbers and, in turn, to the potential appearance of new shell gaps;
- deformations different for the proton and neutron distributions giving rise to new collective modes;
- electric and magnetic giant resonances with strength distributions totally different from those known in stable nuclei;
- in-medium interactions in proton-neutron asymmetric and low-density nuclear matter.

Light-hadron scattering in the intermediate-to-high energy regime (here, typically bombarding energies of 100 – 700 MeV/nucleon are considered) is a well-established method in nuclear-structure physics; its application to beams of exotic nuclei is indispensable. The great nuclear structure potential of light-hadron scattering arises from the fact that, by means of a proper choice of the probe, transitions can selectively be induced (e.g. emphasizing or excluding spin and/or isospin transitions), and the form factors are sensitive to the transition multipolarity. Polarized targets allow to be selective not only on the orbital angular momentum but also on the total angular momentum, and therefore gives extra sensitivity on the spin-orbit part of the potential.
A survey of the nuclear structure information, which can be gained from the type of measurements as described here, and as far as relevant with regard to unstable nuclei, is provided in tabular form (Table 1); details on specific reactions are outlined subsequently.
The physics case and the basic experimental scheme addressed in this Letter of Intent was already outlined in the Conceptual Design Report for the International Accelerator Facility for Beams and Antiprotons [CDR01] to which refer including the references cited therein.

Table 1: Nuclear structure information from intermediate-energy scattering off light nuclei

Method (reactions)	**Physical observables**	**Related effects in exotic nuclei**
elastic scattering (p,p); (^{4}He,^{4}He);	nuclear matter radii and distributions	halo; neutron skin; central density; optical potential
inelastic scattering (p,p');($\bar{p}$,p'); (^{4}He,^{4}He')	surface collective states; electric giant resonances; isovector magnetic excitation for (p,p'); analyzing powers	bulk properties in N-Z asymmetric matter; proton/neutron deformation; nuclear compressibility; threshold strength; soft modes
charge exchange (p,n); (d,^{2}He); (^{3}He,t)	spin-isospin excitations; Gamow-Teller; Spin-dipole resonance	(stellar) weak interaction rates; spin excitations; neutron skin
transfer reaction (p,d); (d,^{3}He); (p,t); (d,p)	Spectroscopic factors; Single particle (hole) states; Pair transfer	single-particle structure; spin-orbit; pairing interaction
quasi-free scattering (p,2p);(p,np); (p,p ^{4}He)	single-particle spectral function; cluster knockout	single-particle structure; nucleon-nucleon and cluster correlations; in-medium interactions

1.1.1 Elastic scattering

Elastic scattering, such as (p,p), (α,α), etc. gives access to nuclear potentials and to the size and radial shape of nuclei. Intermediate-energy elastic proton scattering is a standard tool in measuring nuclear matter distributions in stable nuclei and it was already used to determine the nuclear matter density distributions of light exotic nuclei [Alk02]. It will serve in future investigations of skin and halo structures in heavier nuclei far off stability. Fig. 2 demonstrates the high sensitivity of the method as proposed here. The simulation calculation was performed adopting predicted nuclear matter distributions for Sn isotopes [Hof01], applying the Glauber multiple scattering theory, and adopting experimental conditions as expected for the proposed scheme. Keeping in mind that the matter radii of the two ^{120,132}Sn nuclei differ only by 0.13 fm, the precision that can be achieved for r.m.s radii is evident. Obviously, higher moments of the matter distribution such as related to the surface diffuseness, the central density, etc. can be deduced from the analysis of the measured differential cross section.

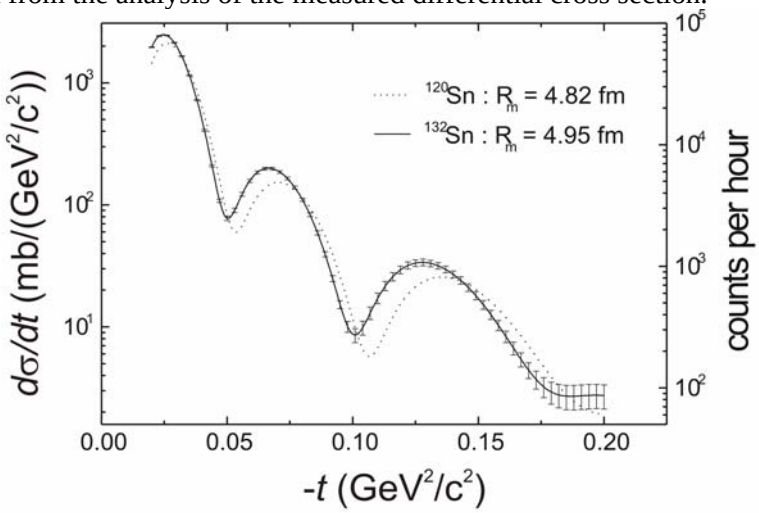


Fig. 2: Differential cross sections dσ/dt versus the four momentum transfer squared -t for proton elastic scattering on ^{120}Sn (dotted line) and ^{132}Sn (solid line) at E = 740 MeV per nucleon resulting from a simulation. The scale displayed on the right-hand axis of the figure and statistical error bars in case of ^{132}Sn correspond to typical experimental conditions as expected at the NESR and a luminosity of 10^{28} cm^{-2} s^{-1}.

1.1.2 Inelastic scattering

Light-ion inelastic scattering allows to trace the evolution of nuclear shape and collective motion over the chart of nuclei. The excitation of low-lying collective states by proton or α-particle scattering probes essentially the isoscalar transition density. By combining with electromagnetic excitation, the proton/neutron content of the transition density can be deduced and thus proton and neutron deformations be separated which may differ substantially from each other in exotic nuclei.
A large proton-neutron asymmetry in a nucleus as well has significant influence on bulk collective motions, i.e., on the strength distributions of giant resonances, and may lead, for instance, to a vibration of loosely bound valence neutrons forming a neutron skin against the remaining core nucleons. Proton inelastic scattering played an essential role in the discovery of spin-excited giant resonances, like the M1 mode, while α-scattering is widely used to study isoscalar modes, such as giant monopole (GMR) or quadrupole resonances [Har01]. A study of the GMR in neutron-rich unstable nuclei will give access to the compressibility of proton-neutron asymmetric nuclear matter. The angular distribution of the GMR in inelastic α scattering is centered at zero degree center-of-mass angle; it is an essential feature of measurements in inverse kinematics, in conjunction with gas jet targets in a storage ring, that these very small center-of-mass angles can be covered.

1.1.3 Transfer reactions

One- or few-nucleon transfer reactions such as (p,d), (p,t), (d,^{3}He), (p,^{3}He), (d,p), etc. provide information on the single-particle neutron and proton structure in nuclei far off stability. Occupation numbers and spectroscopic factors can be deduced. The investigation of single-particle (hole) states and two-particle (hole) states, in particular in the vicinity of unstable doubly magic nuclei, delivers information on effective interactions in these off-stability nuclei. A comparison of cross sections for one- and two-nucleon pickup reactions allows studying nucleon pair correlations. Spectroscopic data and capture cross sections via indirect methods (such as (d,p) neutron transfer reactions) for nuclei participating in the astrophysical r- and rp-processes are essential in understanding the nucleosynthesis pathways. Due to momentum matching criteria for the transferred particle(s) such investigations are most favourably performed at incident energies of about 10-30 MeV per nucleon. In consequence, such measurements require decelerating the ion beams stored in the rings [Ege03]. Present or future ISOL facilities with re-accelerated beams of unstable isotopes may provide higher luminosities, in particular for neutron-rich fission fragments; the proposed scheme here may have advantages in case of shorter-lived isotopes and for neutron-deficient isotopes.

1.1.4 Charge-exchange reactions

The Gamow-Teller (GT) transition is the most basic spin-isopin excitation without angular momentum transfer and plays as an important role in the allowed β-decay caused by the weak interaction. The initial step of the hydrogen fusion reaction leading to nucleosynthesis in stars, the electron-capture reactions leading to stellar collapse, and supernova formation are mediated by the GT transition. A basic understanding for all these processes requires reliable knowledge of the GT strength distribution in nuclei far from the stability line within a large excitation energy range.
Spin-isospin transitions with higher multipolarities are equally important in nuclear processes that happen under extreme conditions, like in a supernova. A study of these excitations in unstable nuclei involved in such nuclear processes is indispensable. Furthermore, there is a correlation between the cross section of the spin-dipole resonance and the neutron-skin thickness of nuclei [Kra99]; this latter quantity is important for constraining the density dependence of the symmetry energy of nuclear matter. Intermediate-energy secondary beams allow studying spin-isospin excitations in unstable nuclei using charge-exchange reactions, such as (p,n), (d,^{2}He), and (^{3}He,t) in inverse kinematics. The kinematically complete experiments (see below) should even enable a substantial suppression of competing background-reaction channels, prohibited in the earlier inclusive-type investigations on stable nuclei.
The use of polarized targets in (^{3}He,t) reactions can be of great help to disentangle the information on different spin-dipole excitations, as well as for the identification of the isovector M1 and $\Delta L=1$ spin-flip modes in sd- and fp-shell nuclei, relevant in the astrophysical context.

1.1.5 Quasi-free scattering

Quasi-free scattering has proven to be one of the most direct and powerful ways of investigating the single-particle properties of a nucleus, such as the separation energies and momentum distributions of nucleons inside the nucleus, in particular for inner-shell orbits [Kit85]. Quasi-free scattering data are also employed to study the effect of the medium on the underlying nucleon-nucleon interaction; in case of exotic nuclei, the environment of proton-neutron asymmetric matter and of low density in extended nuclear surfaces are of particular interest. The quasi-free scattering physics program at the NESR storage ring will focus on several distinct, but related, key experiments:
The single-particle structure of light and medium-mass neutron-rich nuclei is investigated using (p,2p) and (p,pn) reactions. Key nuclei will be nuclei near neutron (sub-)shell closures such as ^{56}Ni (N=28), ^{68}Ni (N=40), and towards ^{78}Ni (N=50); the chains of argon and tin isotopes are also of particular interest. Other investigations focus on the effects in low-density matter, i.e., in neutron halo nuclei and in nuclei exhibiting extended neutron skins.
Clustered structures in exotic nuclei are studied using cluster knockout reactions. Close to the neutron drip line it is predicted that the ground-state structure of nuclei may adopt a highly clustered state. (p,pCluster) knockout reactions may provide a method for the determination of the cluster spectroscopic factor. The evolution of clustering from stability to the drip line is a key test of the theoretical predictions.

1.2 Competitiveness

Until now and presently, a number of experimental attempts were and are undertaken at various laboratories to utilize light hadron scattering with rare-isotope beams. Proton elastic and inelastic scattering, knockout and transfer reactions at low-to-intermediate energies were performed at GANIL (France), GSI (Germany), JINR (Russia), MSU (USA) and RIKEN (Japan). Elastic scattering experiments have been used for matter radii and distribution measurements of light halo nuclei such as ^{6,8}He or ^{11}Li, inelastic scattering experiments provided data on the excitation of bound excited states. Heavy-ion induced knockout reactions have been used to measure spectroscopic factors. In contrast to quasi-free proton scattering, such knockout reactions probe, however, only the asymptotic part of the (valence) nucleon wave function. As far as giant resonances in exotic nuclei are concerned, the present-day technique relies on heavy-ion induced Coulomb excitation, which is restricted, however, to the nuclear dipole response. Light-hadron scattering, together with electron scattering, the standard tools in that respect, could not yet be used.
So far, light-ion scattering measurements were performed for light unstable nuclei only and were of more inclusive type. For heavy exotic nuclei, measurements at low momentum transfer require a different experimental technique. The originality of the present project arises, in essence, from the following aspects:

- The project represents, worldwide, a first attempt to implement nuclear reaction studies with unstable exotic nuclei utilizing heavy-ion storage rings. Windowless thin internal targets are a key prerequisite for studies at low momentum transfer.
- The detector system under consideration (see below) is universal in the sense that it allows to handle a wide class of different nuclear reactions and thus to address numerous physics questions. Technologically, the required Ultra-High-Vacuum compatibility is most demanding and requires non-standard solutions of the detector design.
- The detector system provides the capability of fully exclusive kinematical measurements. This is of interest not only in experiments with exotic nuclei, but also with stable beams. Conventional techniques in the context of light-hadron scattering are of inclusive type to a large extent.

The EXL physics program has some overlap with that proposed in the R3B Letter of Intent as far as light ion scattering is considered there, in particular with regard to quasi-free scattering. For nuclear lifetimes around or below one second, where beam cooling (see below) is not fast enough, measurements at the external target are of preference. For longer lifetimes, cooling and beam accumulation in the storage ring should provide superior conditions.

2. The EXL Detector

2.1 Experimental concept and requirements

For the studies listed in Table 1, exotic nuclei are provided as a secondary beam to be scattered off the light target nuclei (e.g., p, d, ^{3}He, ^{4}He). For a number of studies, e.g., that of the GMR or GT strength, the relevant nuclear structure information is obtained from form factors measured at rather moderate or even small momentum transfer, i.e., at c.m. angles around zero degree. Inverse kinematics implies that the light target nuclei emerge from the reaction with extraordinarily low kinetic energies, around and even below 1 MeV (see Fig. 3). Momentum and energy transfer need to be extracted from the kinematical quantities of the light target recoil, because of the high projectile energy and because of the fact that the heavy projectile-like fragment often disintegrates. In order to extract reliable information on excitation energy (required resolution ~ 0.1 MeV) and on center-of-mass scattering angle (required resolution: a few mrad), kinetic energy and scattering angle of the target recoil in the laboratory frame need to be measured down to a resolution of 100 keV and 1 mrad, respectively.
Additional mandatory prerequisites are a) a small spread in kinetic energy (T_b) of the secondary ion beams ($\delta T_b/T_b \sim 10^{-4}$) and b) a low target thickness in order to let the target recoils escape and to keep small-angle multiple scattering on a tolerable level (typically, the effective target thickness, including windows, needs to be below 1 mg/cm^2). Low target thickness yields low reaction luminosities; transferring the beam into a storage ring and thus benefiting from its re-circulation can overcome this problem.

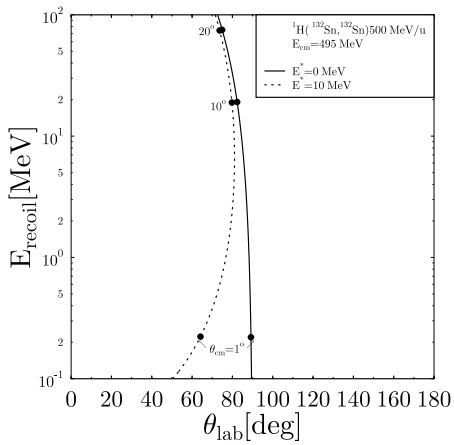


Fig. 3: Kinetic energy of recoiling ^{1}H target nuclei versus laboratory scattering angle for (in)elastic scattering of a ^{132}Sn beam of an energy of 500 MeV per nucleon. Respective center-of-mass angles are indicated.

The CR-RESR-NESR storage-ring complex planned at the Facility for Antiproton and Ion Research (FAIR) provides optimal conditions for inverse light-ion scattering experiments, the most relevant features are:

- Luminosities even above 10^{28} cm^{-2} s^{-1} can be achieved, see Table 2; further developments on internal targets may even yield improved values. Cross sections of 0.1 – 100 mb/sr are typical for reactions as listed in Table 1 and thus very reasonable reaction rates are expected. The windowless internal target avoids background reactions.
- Stochastic pre-cooling in the CR combined with electron cooling in the NESR provides stored beams of excellent quality with regard to emittance and momentum spread, matching the requirements (see above) for kinematical measurements of the target recoils.
- The energy of the stored beam is variable within a wide range up to 740 (depending on magnetic rigidity even up to 820) MeV per nucleon. For isotopes with a lifetime of at least seconds deceleration down to tens of MeV per nucleon becomes feasible without substantial deterioration

of beam intensity and quality. This wide range in beam energy suits well to the experiments under discussion.

- Secondary beams produced in fragmentation or fission reactions may have sizeable contaminants of nuclei in long-lived isomeric states. Measuring during distinct time intervals after injection into the ring allows disentangling such beam components (an interesting scheme of separating isomeric beams by a beam-scraping technique is proposed in another Letter of Intent to FAIR[LEB04]).

The main objectives of the experimental scheme as proposed in this Letter of Intent are a) optimizing the luminosity, b) providing a high-resolution detection system with nearly full solid-angle coverage and detection efficiency, c) providing a detector setup for kinematically complete measurements, thus covering simultaneously all reaction channels of interest.
At present, only a first concept of the detection system can be given; the participating groups will work out the final conceptual and technical design subsequently, see section 3.4.

Table 2 Expected luminosities in the NESR storage ring adopting an internal target density of 10^{14} hydrogen atoms/cm^2 and for a beam energy of 740 MeV per nucleon.

Nucleus	**Rate after production target [1/s]**	**Lifetime including losses in NESR [s]**	**Luminosity [cm^{-2} s^{-1}]**
^{11}Be	2 x 10^9	36	> 10^{28}
^{46}Ar	6 x 10^8	20	> 10^{28}
^{52}Ca	4 x 10^5	12	2 x 10^{26}
^{55}Ni	8 x 10^7	0.5	5 x 10^{26}
^{56}Ni	1 x 10^9	3800	> 10^{28}
^{72}Ni	9 x 10^6	4.1	1 x 10^{27}
^{104}Sn	1 x 10^6	51	2 x 10^{27}
^{132}Sn	1 x 10^8	93	> 10^{28}
^{134}Sn	8 x 10^5	2.7	3 x 10^{25}
^{187}Pb	1 x 10^7	34	2 x 10^{28}

2.2 Detector components and environment

The main ingredients of the experimental scheme are briefly described as follows.

2.2.1 Stored and cooled beams

Secondary beams are transferred from the fragment separator (Super-FRS) to the collector ring (CR) at a fixed energy of 740 MeV per nucleon. The main task of the CR is the efficient collection and stochastic pre-cooling to a relative momentum spread around 10^{-4} and an emittance of 1 mm mrad within a cooling time of a few hundreds of milliseconds. The beam quality can be further improved by means of electron cooling in the new experimental storage ring (NESR). Electron cooling serves as well to compensate the beam heating due to its interaction with the internal target. Using rf cavities inside the RESR, a third storage ring in between the CR and NESR, the beam can be decelerated thus providing a variable energy (rf cavities are also installed at the NESR). For example, only about 1 second is needed to decelerate from 740 to 100 MeV per nucleon. This procedure results in an increase in emittance that needs to be counteracted by electron cooling.
Luminosity at the internal target is gained due to the circulation frequency (~ 1 MHz) of the stored beam. An important option to achieve optimum luminosity is fast beam stacking. The limitation for this scheme is given by the beam lifetime that is determined by the nuclear lifetime and losses due to atomic charge exchange processes in the internal target, in the residual gas in the ring, and in the electron cooler [Ege03]. Some representative examples are given in Table 2. Multi-charge state operation of the NESR may increase the effective beam lifetime.

2.2.2 Internal target

Gas/cluster-jet or pellet targets with densities of 10^{14} - 10^{15} hydrogen or helium atoms/cm^2 are envisaged (targets of heavier elements can be provided as well). Such densities are within reach on the basis of present-days knowledge and may still be improved. Cluster-jet targets, for instance, exist at the ESR (GSI) and at the CELSIUS (TSL) storage rings; a pellet target was developed at the CELSIUS ring. Using thin-foil or fiber targets can reach higher densities; it needs to be explored, however, if higher densities are compatible with the demands on beam quality (deteriorated by multiple passage through the internal target). The energy loss in passing a thin-foil target could be compensated by rf cavities; the NESR rf cavities would allow to eliminate a few keV energy loss per nucleon per single passage. Whether the degradation of beam momentum spread can be tolerated depends on the specific experiment and the optimum target thickness has to be found from simulation studies. At low momentum transfer, the low target recoil energies prohibit a vertex reconstruction. The interaction point is sufficiently defined transversally by the beam diameter; longitudinally along the beam direction, however, the extension of the jet target determines the spatial accuracy of the interaction point. Developments are required to minimize the jet diameter to about 1 mm. Alternatively, a diaphragm narrowing down the effective interaction zone along longitudinal direction could be used, but reduces the effective luminosity. It will also be considered if polarized targets can be implemented. Polarized ^{3}He-targets with polarizations of up to 75% are available today [Heil] and internal polarized ^{3}He targets have been used at several laboratories in the past (NIKHEF, Bates, Hermes).

2.2.3 Target recoil detector

The main requirements are high resolution for momentum and energy of the recoiling target nuclei and a low detection threshold. A very schematic view of the target recoil detector is shown in Fig. 1. At high momentum transfer (forward angles), tracking of the target recoil is feasible, but prohibited at small momentum transfer.

Two layers of radiation-hard (double-sided) Si strip detectors measure position and kinetic energy and time of flight. For low recoil energies not allowing for tracking, the accuracy of the measured scattering angle depends on the extension of the gas-jet target along beam direction (see above) and the distance between target and detector. In that case, i.e., at recoil angles near 90°, the target-detector distance will range in between 0.5 m to 1 m; detection thresholds around 100 keV are required. At more forward angles, the target recoils can be tracked in two layers of Si detectors that can gradually be placed closer to the jet target. The position resolution of the Si detectors has to be adjusted to the required angular resolution of about 1 mrad requiring 100 - 200 μm pitch. Eventually, the recoil ions will be stopped in organic scintillation detectors, e.g. (cooled) CsI crystals, serving also other purposes (see below). The target recoil detectors are thus operated as (Δ)E-(Δ)E-E telescopes. The optimum thickness of each of the three detectors varies with recoil angle and more detailed simulations for different reaction scenarios are required for a final design. At least the first layer of the target recoil detector needs to be operated under the ultra-high vacuum (UHV) conditions of the storage ring, imposing severe requirements upon the detector material. Groups working at CELSIUS gained experience with an UHV compatible Si detector array [CHICSI]. Tests with UHV compatible Si detectors are currently also performed at the ESR at GSI. The Saclay group has built a large array of Si-Si(Li)-CsI telescopes with integrated signal processing, with characteristics rather similar to the recoil detector here [MUST]. The UK groups have built a Si strip detector system for direct reaction studies [TIARA]. Energy resolutions of about 50 keV, time-of-flight resolutions of 200 ps, and a detection treshold of 100 keV seem achievable.

It is intended to subtend the forward hemisphere in a cylindrically symmetric (except for provisions for the internal target) geometry. It is still under discussion to which extend the backward hemisphere should be covered as would be required if transfer reactions of type (d,p) are considered. Detailed simulation studies will be performed in order to find the optimum detector characteristics and geometry, taking economical aspects into consideration.

Electrons released (with energies up to MeV's) from the gas target will be by orders of magnitude more abundant than recoil ions and need to be transported out of the recoil-detector area by a magnetic field along beam direction.

2.2.4 Gamma-rays and slow neutrons

The inorganic scintillation detectors (see above) serve as well for detection of gamma rays emitted from the excited projectile residue. A rather high granularity is required in order to cope with gamma-ray Doppler broadening effects; an energy resolution of about 2 % is envisaged. A CsI barrel of 144 elements with a geometry similar to the one considered here is is existing at GSI. For some experiments, it is under discussion to install Ge detectors with better resolution such as an array composed out of AGATA detector modules, see also [LEB04]. Likewise, a dedicated fast organic scintillation detector for precision neutron measurements in (p,n) reactions is proposed, prototype detectors are already tested.

2.2.5 Forward spectrometer

Mass and charge of the heavy projectile fragment needs to be identified and its momentum measured. For that purpose, it is foreseen to utilize bending magnets of the storage ring for the analysis of the fragment magnetic rigidity in combination with energy loss, time-of-flight, and position measurements; see Fig. 1 for a schematic view. It is envisaged to achieve a (transversal and longitudinal) momentum resolution of the order of 10 – 50 MeV/c. Preliminary considerations indicate that a corresponding value of $\Delta p/p \sim 10^{-4}$ can be achieved, but detailed ion-optical studies need to be performed. Excitation of the projectiles into the continuum leads to particle emission, i.e., essentially neutrons and light charged particles around beam rapidity. The envisaged detector scheme comprises their position and time-of-flight measurements using fast scintillators, in case of neutron detection involving converter material or, alternatively, appropriate inorganic scintillation material. Accurate position measurements for charged particles are achieved in drift chambers. It is intended to exploit recent developments towards ultra-fast phototubes and fast scintillating material for time-of-flight resolutions below 100 picoseconds; depending on the achievements, a flight path of 5 –10 meter will be needed in order to gain a momentum resolution below $\Delta p/p \sim 10^{-2}$ with a detector compact array. This would allow reconstructing the excitation energy of the projectile residue to an accuracy of about 1 MeV by means of the invariant-mass method, thus delivering information redundant, although less accurate, to that obtained from the target-recoil kinematical measurement.

2.2.6 Trigger and data acquisition

Electronic detector readout schemes, trigger systems, and data-processing procedures need to be developed hand-in-hand. The high granularity of the position-sensitive detectors for the target recoils demands on-board signal processing; it is explored whether customized wafers are available, but the demand of operation under UHV condition may require dedicated developments. The fast timing measurements for the projectile and its ejectiles demand the design of high-resolution timing circuits.
Given the luminosities and total interaction cross sections, nuclear reaction rates hardly exceed 10^5 per second; fast coincidence requirements among the various detector components reduce the trigger rate down to 10^4 s^{-1} or less. Thus a conventional scheme of transferring pre-selected data to a higher-level hierarchy or directly to storage could be implemented. More advanced schemes, nevertheless, are considered where signals from all detectors are autonomously detected, pre-processed, and buffered by FPGA, DSP and CPU based computation boards. Higher-level trigger selections may thus be made on-line in the cross-linked boards. Finally, only relevant and preprocessed information, synchronized by timestamps, is transferred. In such developments, one may benefit from the developments that are currently started within the Future DAQ Joint Research Activity from the I3HP Initiative of the 6th EU framework (2004-2006) for the CBM, PANDA and COMPASS experiments. As indicated in the introduction to the NUSTAR letter of intents, it is envisaged to develop a common basic DAQ scheme at the SUPER-FRS facility.

2.2.7 Physics performance

A simulation software will be developed on the basis of which feasibility demonstrations for the specific reaction studies of interest can be provided in a technical design report. In parallel, prototype detectors will be built and tested and the electronic read-out techniques will be developed. An experimental

storage/cooler ring (ESR) for heavy ions is at this moment operational at GSI which is linked to the FRS radioactive-beam facility. The ESR will be instrumental in developing the EXL detector, in performing feasibility studies and first experiments. It should be noticed that the EXL concept provides the means for kinematical fully complete measurements, under most circumstances not achieved in conventional light-ion scattering experiments with stable target nuclei. It may thus add substantially to the physics information derived from light-hadron scattering experiments applied to *stable* isotopes and scientifically valuable experiments can already be performed at the ESR.

2.2.7 Synergy with other Letters of Intent

There are, in part, common interests as far as the physics goals are concerned with other submitted Letters of Intent, in particular with the LoI on external target (R3B LoI [R3B04]) and on electron scattering experiments (ELISe LoI [ELI04]). The R3B LoI includes light-ion scattering complementing the storage ring experiments discussed here, covering the part of large momentum transfer. A target recoil detector, although of different specification, is required as well and it is envisaged to develop a common electronic read-out scheme. In case of electron scattering at the electron ring intersecting the NESR [ELI04] and for the proposed antiproton-ion collider [PBAR04], a forward spectrometer for the projectile fragments built into the NESR lattice is required, similar to the one discussed here. Both, from the common physics goals and similar development lines for subsets of the setups, a close collaboration among the participants of R3B, EXL and ELISe is most natural, and is manifested in the partial overlap in personnel.
Synergy with LoI's outside NUSTAR is evident as well: The internal target will be used by atomic physics groups (AP), these groups are in part also planning for a (UHV) detector system similar to the recoil detector and as well will use a fragment forward spectrometer; a close collaboration is envisaged and discussions were already started. To our knowledge, silicon tracker devices (here, the target recoil detector) are substantial devices in both the PANDA and the CBM LoI; PANDA is also aiming at high-density internal targets. a collaboration in particular on the read-out schemes should be achieved.

3. Implementation

3.1 Experimental area and radiation environment.

The EXL apparatus needs to be installed at one of the four straight sections of the NESR. Since reaction rates are low, no specific demands on radiation shielding beyond that needed for NESR operation seem to appear. Around the cluster-jet (or other) target, an area of 150 m^2 is requested , i.e., 5 m wide on each side of the beam line, 10 m downstream the beam, and 5 m upstream the beam. The height of the beam line above ground should be 2.5 m. Other groups will use the same NESR straight section as seen from the submitted LoI's. A first discussion with representatives of such groups resulted in the suggestion that only one target station together with a scheme of replacing the various setups including the internal target would be preferable over solutions with multi-target stations. In consequence, parking room for the detection systems in immediate neighborhood to the experimental area is needed, in the case of EXL about 100 m^2. This storage area should moreover serve for off-line detector testing and maintenance etc., and should have access independent from operation of the NESR (or other accelerator components) and thus sufficient radiation shielding. Space for on-line data taking (~ 150 m^2) and additional office space (~ 200 m^2) to host the collaboration during experiment should be provided; to some extent, it might be shared with other collaborations.

3.2 Cost estimate

Only a rough cost estimate can be provided (Table 3), based on a tentative design involving a target recoil detector of 3 x 10^5 Si strip readout channels and 0.2 m^3 CsI scintillation material (1200 photodiodes), a forward ejectile detector of inorganic scintillation material (0.4 m^3) plus charged particle detection, a forward heavy-ion spectrometer, and a jet target and UHV chamber.

Table 3. Preliminary cost estimate

Task	**Cost estimate** (kEuro)
Target recoil detector	
Si micro strip	1,600
CsI	850
Forward spectrometer	
Light charged particles	150
Inorganic scintillator (neutron)	1,100
Heavy ion detectors	100
Trigger electronics, slow control, data acquisition	200
Jet target, pumping units, vacuum chamber	1,200
Overhead (10%)	600
Total:	**5,800**

3.3 Organisation and responsibilities

All participating research teams have experience with regard to scientific or technological aspects addressed in this LoI and will participate according to their expertise and physics interests. Three of the participating institutes operate storage-cooler rings for hadrons or heavy ions (COSY at FZ- Jülich; CELSIUS at TSL, Uppsala; ESR at GSI, Darmstadt).
A Coordination Board (CB) will be formed out of representatives of the participating groups. At its next meeting, the CB will name the spokesperson and deputy of the EXL collaboration. The main duties of the CB are to monitor the progress of the project and the quality of the developments, to ensure the reporting procedure according to the demands of FAIR as well as publication of results, and to guarantee optimal communication between the participants and thus economical usage of the provided funding. For the monitoring purpose, the CB will request internal reports from the participants at regular intervals.
To guarantee that various components of the project are properly dealt with, working groups are formed, which are responsible for the different parts and report to the CB. Responsibilities for the various tasks are given in Table 4 as agreed upon in collaboration meetings so far, but should be considered as tentative, a final decision will be taken after the CB has been formed.
External expert advice will be asked for when deemed necessary by the CB.

Table 4: Tasks and responsibilities.

Task	**Group**
Realistic physics scenarios and key experiments: - nuclear structure - nuclear (astroph.) reactions	 Madrid, Milano, GSI UK, UNIBAS
Physics/detector requirements	UK, Mainz, GSI
Storage Ring	GSI
Internal target	TSL , FZJ, GSI
Target recoil detector and UHV	CEA, UK, Mainz, FZJ, IPN, TSL, Lund, GSI
Gamma detector Low-energy neutrons	UK, TUM, GSI ATOMKI
Fragment spectrometer	GSI, TUM, Dubna
Forward ejectiles	GSI, Gatchina
Readout electronics, DAQ	CEA, UK, TUM, GSI

3.4 Time schedule

The implementation of the EXL detector and ancillary components involves various steps, the general time line of the project is as follows: the implementation phase covers a period of 6 years (2004 – 2009). The conceptual design of the detector system will be finalized end of 2004. The technical developments of the subtasks (e.g. improvement of internal targets, detector prototypes, electronics and read-out schemes) and test measurements will be performed until end of 2006 and a technical report is delivered. It is intended to show the proof of principle of all subunits until 2007 and subsequently realize the full system. According to present planning for FAIR, the ESR at SIS18 should remain operational until 2009. Thus, for a period of about two years, the EXL detector system (or major components of it) can be utilized for first experiments at the already existing storage ring. For such purposes, stable or near-stability beams will be used, in the latter case one benefits already from the SIS18 intensity upgrade by about one order of magnitude as planned for 2006/2007. At the new facility, the instrument proposed here can be fully exploited in experiments with stored beams of exotic nuclei much further away from the valley of stability.

3.5 Beam time considerations

A typical experiment requires about two weeks of beam; it may be estimated that the requests for EXL experiments add up to about two month per year. Storage and accumulation of ions followed by measurement phase allows sharing the beam with other experiments to some extent, and the effective beam request may thus reduce. A parallel antiproton program, however, is prohibited since for most of the experiments the full storage ring complex is needed. Only for experiments with long-lived isotopes (allowing for the longer period of electron cooling without stochastic pre-cooling), the secondary beam can be transported from the Super-FRS directly into the NESR.

References

[Alk02] G.D. Alkhazov et al, Nucl. Phys. A 712 (2002) 269.
[CHICSI] L. Westerberg et. al., Nucl. Instr. and Meth. A 500 (2003) 84.
[CDR01] www.gsi.de/zukunftsprojekt/index.html
[Ege03] P. Egelhof et al., Phys. Scripta T104 (2003) 151.
[ELI04] Letter of Intent for ‘Electron-Ion Scattering in a Storage Ring (eA Collider) (ELISe)’
[Har01] M.N. Harakeh and A. van der Woude, Oxford Studies in Nucl. Res., Vol.24 (2001)
[Heil] W. Heil, University Mainz, priv. comm.
[Hof01] F. Hofmann, *et al.*, Phys. Rev. C 64, 034314 (2001).
[Kra99] A. Krasznahorkay et al., Phys. Rev. Lett. 82 (1999) 3216.
[Kit85] P. Kitching et al., Adv. Nucl. Phys. 15 (1985) 43.
[LEB04] Letter of Intent for the ‘Low-Energy Branch of the Super-FRS’.
[MUST] Y. Blumenfeld et al., Nucl. Instr. And Meth. A 421 (1999) 471.
[PBAR04] Letter of Intent for an ‘Antiproton-Ion Collider: A tool for the measurement of neutron and proton rms nuclei’.
[R3B04] Letter of Intent for ‘A versatile setup for kinematical complete measurements of Reactions with Relativistic Radioactive Beams (R^3B)’.
[TIARA] www.ph.surrey.ac.uk/npg/tiara/

Letter of Intent for

Electron-Ion scattering in a Storage Ring (eA Collider)

ELISe Collaboration

April 12, 2004

Abstract

We propose to study the structure of exotic nuclei in electron-ion scattering experiments. The ELISe objective is to capitalize on elastic, inelastic, and quasi-free electron scattering by using intersecting ion and electron storage rings and an electron spectrometer operating in conjunction with a detector system for reaction products, providing high resolution and large solid angle coverage. The experiment is foreseen to be installed at the New Experimental Storage Ring (NESR) at FAIR where cooled secondary beams of radioactive ions will collide with an intense electron beam circulating in a small electron storage ring. In the frame of the NuPECC working group on the "Next Generation Radioactive Beam Facility in Europe" such a small eA collider for nuclear structure research has been strongly recommended.

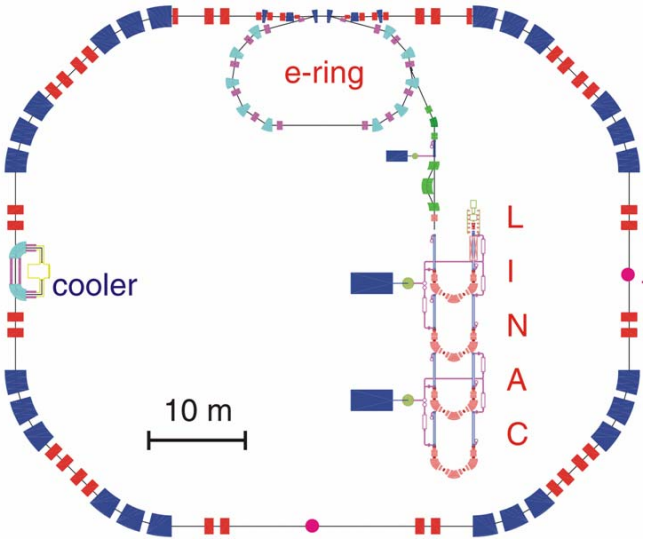


Fig. 1: Schematic view of the electron-ion (eA) collider consisting of the NESR storage-cooler ring, the electron LINAC, and the electron (or antiproton see [pbarA 04]) storage ring.

List of Collaborators

Institut für Physik, Universität Basel, Basel, Switzerland (**BAS**)
K. Hencken, J. Jourdan, B. Krusche, F. Rauscher, D. Rohe, D. Trautmann

Budker Institut of Nuclear Physics, Novosibirsk, Russia (**BINP**)
I.A. Koop, M.S. Korostelev, P.V. Logatchov, I.N. Nesterenko, A.V. Otboev, V.V Parkhomchuk, V.M. Pavlov, E.A. Prevedentsev, D.N. Shatilov, P.Yu. Shatunov, Yu.M. Shatunov, S.V. Shiyankov, A.N. Skrinsky, A.A. Valishev

CERN, Geneva, Switzerland (**CERN**)
L. Fraile

Chalmers Tekniska Högskola and Göteborgs Universitet, Göteborg, Sweden (**CTH**)
H. Johansson, B. Jonson, G. Nyman

Instituto de Estructura de la Materia, Madrid, Spain (**CSIC**)
M.J.G. Borge , E. Garrido, E. Moya de Guerra, P. Sarrigurem

University of Sevilla, Sevilla, Spain (**ESP**)
J.A. Caballero

University of Granada, Granada, Spain (**ESP**)
E. Amaro, A. Lallena

Gesellschaft für Schwerionenforschung, Darmstadt, Germany (**GSI**)
T. Aumann, F. Becker, P. Beller, K. Boretzky, A. Dolinskii, P. Egelhof, H. Emling, B. Franzke, H. Geissel, A. Kelic, N. Kurz, F. Nolden, K.-H. Schmidt, H. Simon, M. Steck, H.Weick

Institute of Physics and Power Engineering, Obninsk, Russia (**IPPE**)
S.P. Kamerdzhiev, E.V. Litvinova

Joint Institute of Nuclear Research, Flerov Laboratory of Nuclear Reactions, Dubna, Russia (**JINR**)
A.G. Artukh, Yu.M. Sereda, S.A. Klygin, Yu.G. Teterev, A.N. Vorontzov, A.E. Korchagin, S.V. Polovnikov

Joint Institute of Nuclear Research, Laboratory for Nuclear Problems, Dubna, Russia (**JINR**)
I.N. Meshkov, E.M. Syresin, I.A. Seleznev

Russian Research Centre, Kurchatov Institute, Moscow, Russia (**KI**)
L.V. Chulkov, L.V.Grigorenko, V.A.Volkov

Sektion Physik der LMU München, München, Germany (**LMU**)
O. Kester

Institute for Nuclear Research , Moscow, Russia (**RAS**)
V.G.Nedorezov, V.P.Lisin, A.A.Turinge, A.L.Polonski, A.N.Mushkarenkov, N.V.Rudnev

RI-Beam Science Laboratory, Discovery Research Institute, Wako, Saitama, Japan (**RIKEN**)
T. Suda

Technische Universität Darmstadt, Darmstadt, Germany (**TUD**)
J. Enders, T. Nilsson, A. Richter, G. Schrieder, A. Zilges

Universidad Complutense, Madrid, Spain (**UCM**)
J.M. Udias Moinelo

Institut für Kernphysik, Johannes-Gutenberg-Universität, Mainz, Germany (**UGM**)
H. Merkel, M. Distler, U. Müller

Daresbury Laboratory, United Kingdom, (**UK**)
R. Lemmon

University of Liverpool, United Kingdom, (**UK**)
M. Chartier

University of Manchester, United Kingdom, (**UK**)
D. Cullen

University of Surrey, Guildford, United Kingdom (**UK**)
W. Catford, J. Al-Khalili, R. Johnson, P. Stevenson

University of York, York, United Kingdom (**UK**)
C. Barton, D. Jenkins

Wright Nuclear Structure Laboratory, Yale University, USA (**WNSL**)
A. Heinz

Contactperson: H.Simon (h.simon@gsi.de)
Deputy: L.V. Chulkov (l.chulkov@gsi.de)

Contents: Electron-Ion scattering in a Storage Ring (eA Collider)

1 Physics case

1.1 Research objectives

The advantages of using electrons in nuclear structure investigations, in essence, arise from the fact that electrons are point-like particles (constant formfactor) and that the electron-nucleus interaction is relatively weak and theoretically well described. Multiple scattering effects can usually be neglected and the scattering process is described in terms of perturbation theory. Since the reaction mechanism is well under control, quantities such as nuclear charge distributions, transition densities, etc., can be deduced reliably from measured cross sections. A certain process can be chosen by proper selection of transferred energy and momentum which can be varied independently from each other. For all processes discussed in the following one can determine form factors. In the case of elastic scattering, they are related to the charge density distributions. For inelastic scattering they are connected with different transition multipolarities of the excitations and offer a unique way to study collective motion in unstable nuclei. At larger energy and momentum transfer quasi-elastic scattering on nucleons contributes increasingly. The availability of an electromagnetic probe for radioactive ion beams is an intriguing approach with a wide and unique discovery potential for nuclei far off stability [1]: Itemizing only the main physics aspects (see also Table 1), one can:

- **(a)** Obtain charge distributions for exotic nuclei from elastic electron scattering.
- **(b)** Get access via inelastic electron scattering to low-lying collective states, giant resonances, and (new) collective (soft) modes with a high selectivity to different multipolarities
- **(c)** Study electro fission likewise
- **(d)** Study direct reactions induced by quasi-free scattering such as (e,e'N), and cluster knockout providing information on the internal nuclear structure and nucleon-nucleon correlations.

Since the pioneering experiments of Hofstadter [2] electron scattering on nuclei has contributed significantly to reveal the structure of stable nuclei. For unstable exotic nuclei, this probe could up to now not be applied. The electron-nucleus collider (eA Collider) will give access to scattering studies also on radioactive species, thereby opening up a new field of electron scattering. Due to the limited luminosities achievable with radioactive beams, first generation experiments will focus on measurements of the nuclear charge distribution via electron elastic scattering [3,4]. Radius measurements of proton and neutron distributions at very low luminosities can be performed, using antiprotons. Studies of the hyperfine structure and isotope shift of atomic states, in particular including laser spectroscopy studies [5,6], give information on relative charge radii, but higher generalized momenta of the charge density distribution are not accessible as well. While measurements of the interaction of radioactive beams stored at NESR with gaseous (^{4}He, $^1H_2$) internal targets will provide very precise information on nuclear matter density distributions, elastic electron scattering with colliding beams will yield charge density distributions. By combining the two methods it will be possible to determine proton and neutron distributions separately for a large number of radioactive isotopes. The ground state densities reflect the basic properties of effective nuclear forces, and an accurate description of these distributions is one of the primary goals of nuclear structure models. The knowledge of nuclear matter and charge density distributions for very proton- and neutron-rich nuclei is most important for deriving the equation of state (EOS) [7] for proton-neutron asymmetric nuclear matter, the neutron or proton skin thickness constraints significantly the parameters of the symmetry energy, while from the surface diffuseness the spin orbit potential can be derived.

It is very important to extend the study of the dominant collective excitations of nuclei, the giant resonances (GR), to β-unstable nuclei. The studies of these resonances give access to specific terms of the EOS of asymmetric nuclear matter. Large proton and neutron excess significantly influences the collective motions in nuclei. Significant modification of strength distributions in light, very neutron-rich nuclei were already observed for the dipole giant resonance (GDR), but are predicted for other multipole modes as well. GDR data were obtained from heavy-ion Coulomb excitation; inelastic electron scattering allows selecting the multipole of electric (and magnetic) giant resonance modes. Electro-induced nuclear fission studies are of special interest here, as it is best suited to study the dynamic properties of cold and moderately excited nuclear matter. At low excitation energies, the onset of dissipation in a super-fluid Fermionic system and the influence of quantum-mechanical structure on a large-amplitude collective

motion can be studied. Nuclear fission is also a unique tool to explore shell effects at extreme deformation. In addition, fission probabilities yield rather direct information on the influence of nuclear structure on nuclear level densities.

The process where an individual nucleon is knocked out off nucleus probes the single-particle structure to be probed. Coincidence measurements (e,e'N) can give detailed information on the combined nucleon-hole energy and momentum distribution, the so-called spectral function, in the target nucleus. The (e,e′p) reaction has been developed into a precision tool for measuring spectroscopic factors of proton single particle states in well-bound stable nuclei [8] and has resulted in a substantial body of knowledge about inner-shell proton orbits (or "deep-hole states"). The results, for deep-hole proton states in nuclei from A=6 to 209, are that the (e,e′p) reaction measures spectroscopic factors that are lower by a factor of 0.50-0.65 than those calculated in the shell model. This systematic reduction is believed to arise from correlation effects, including the short-range part of the nucleon-nucleon interaction [9]. Quasi-free electron scattering is considered as superior, e.g., compared to proton-induced quasi-free scattering or transfer reactions. Again, the reason is that multi-step processes are less likely to occur in electron scattering compared to scattering involving strongly interacting probes. Such studies should be seen in the context of shell re-arrangements in nuclei far away from stability as expected from theoretical calculations.

Kinematically complete experiments where, in contrast to conventional electron scattering, all target-like reaction products are detected, would become feasible for the first time (see below), allowing a clean separation of different reaction channels as well as a reduction of the unavoidable radiative background seen in conventional experiments. Therefore, even applications using stable isotope beams may be of interest.

Table 1: Nuclear structure information from electron scattering.

Experimental method (typical reactions)	**Physical observables**	**Related specific effects**
Elastic scattering (e,e)	nuclear charge radii and their higher moments, charge density distributions	Core size in neutron rich nuclei, core polarizability, Central density
Inelastic (e,e') scattering with the detection of the decay products.	surface collective states; electric giant resonances; isovector analyzing powers; Fission	giant resonances and (new) collective (soft) modes with a high selectivity to different multipolarities; large scale collective motion.
Quasi-free scattering (e,e'N); (e,e'C) in complete kinematics	binding energies for different shells, spectroscopic factors, spectral functions.	single-particle structure; spin-orbit; shell effects; pairing interaction

1.1.1 Elastic scattering

For exotic nuclei, which, in contrast to stable nuclei, are more extended and dilute and where spatial proton and neutron distributions do not overlap any longer, it is essential to know radius and higher moments of these distributions simultaneously.

The techniques used to extract charge distributions from the measured elastic form factor are well established and can be grouped under two basic approaches. In the first approach one solves the direct scattering problem parametrizing the charge distribution. The respective parameters are fitted to the experimental cross sections. Good descriptions of the experimental data were obtained with analytical expressions of the density depending from few parameters (e.g the Fermi distribution). The parameters are related to the characteristics of the shape of the density, for example the half-density radius, the diffuseness, the central depression. The reliability of such density parameterization has been proven by analyzing available electron scattering data [3, 4]. As an example, the sensitivity of the elastic scattering cross section to variations in radius and diffuseness parameters is shown in Fig. 2. Other, so-called model

independent methods, are based upon the expansion of the charge density on a complete set of orthogonal functions. The coefficients of the expansion are changed in order to reproduce the experimental cross section. Recently a new method was successfully applied with the nuclear charge distributions generated by solving the Schrödinger equation with a mean-field potential expanded in terms of Hermite polynomials.

Covering a wider region of *q* gives more detailed information on these density distributions, but requires as well higher luminosities. In the case of light nuclei it is possible to expand the form factor *F(q)* at small *q,* where contribution from inelastic scattering are expected to be negligible, and to determine the root-mean-square (rms) charge radius $< r^2 >^{1/2}$ in a model independent way, already at comparatively low luminosities. This method could be used in first generation experiments prior to the advent of a sophisticated spectrometer setup.

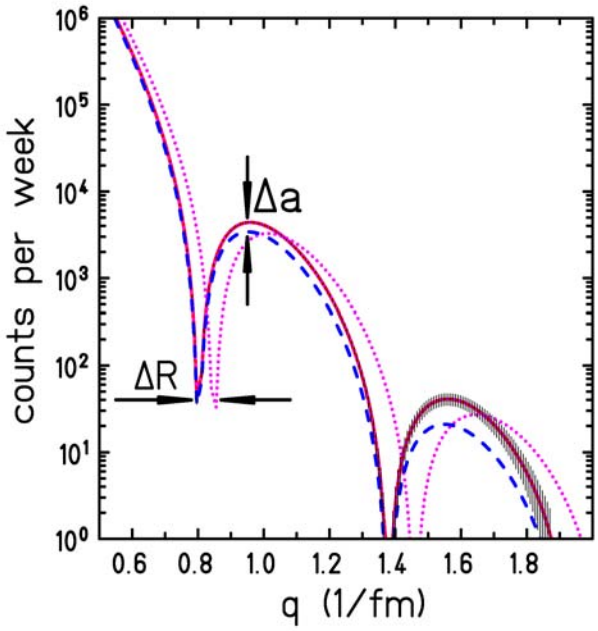


Figure 2: Illustration of the sensitivity of the elastic scattering cross section and thus a typical yield for experiments to a change in the nuclear charge radius R *and diffuseness parameter* a*. The solid curve shows the dependence of the yield on the momentum transfer* q *for* ^{132}*Sn under simplified model assumptions. The dashed curve is obtained increasing* a *by 0.15 fm and shows the variation in slope in that case. The dotted line corresponds to a charge radius increase of 5% and the related shift of the first minimum towards higher momentum transfer. The data are simulated for the* ^{132}*Sn(e,e) elastic scattering at a luminosity of* 10^{28} $cm^{-2}s^{-1}$*, as expected for 1 week eA collider experiments.*

1.1.2 Inelastic scattering

Inelastic electron scattering is an excellent tool for spectroscopy of bound and unbound states in nuclei. Since transitional form factors have different *q* dependence with different multipolarity, by varying the momentum transfer specific multipoles can be excited and thus a selectivity to spins is achieved. This can be seen in Figure 3, where the squared transition form factors for different multipolarities are shown together with the elastic form factor. The inclusive spectra of inelastically scattered electrons generally show a large background from the elastic radiation tail. Measurements with coincident detection of decay products (e,e′X) present a far more powerful tool to selectively study different multipole resonances and their subsequent decay (here the large elastic radiation background is completely suppressed). In colliding beam experiments, the heavy recoils, after emission of a few nucleons, can be detected in 4π geometry using a dipole magnet of the storage ring as magnetic analyzer. Deformations (prolate, oblate, triaxial) can be already deduced from the shape of the giant resonance excitation energy spectra. Fission experiments at the future eA collider will profit from several advantages compared to the previous studies. The high-resolution measurements of the mass, the atomic number and the velocity of fission fragments, already established in inverse-kinematics experiments at GSI, will be combined with the high-precision information on the excitation energy of the fissioning system obtained with the use of tagged photons in the electron – heavy-ion collider. Results of a successfully performed fixed target electron scattering experiment together with a description of the hereto related experimental difficulties can be found in [10]. In electro-fission the angle between fission fragments is only about a few degrees, consequently both fission fragments can be detected and analyzed in coincidence.

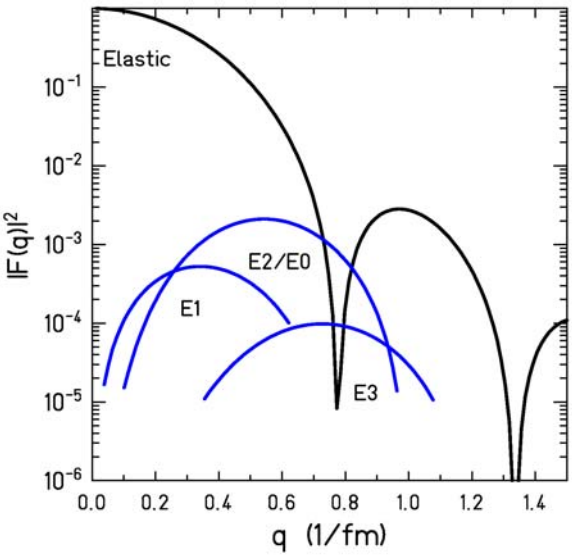


Figure 3: Sensitivity of the formfactors with different multipolarities (monopole, dipole, quadrupole and octupole transitions) to the transferred momentum. For sake of clarity secondary diffraction peaks have been omitted.

1.1.3 Quasi-free scattering

In a region where the squared relativistic momentum transfer Q^2 is close to $2m\omega$ (here m and ω denotes the nucleon mass and transferred energy, respectively) electron scattering is dominated by the interaction with the individual nucleons inside a nucleus. The process where incoming electron directly knocks out an individual nucleon from the target nucleus results in a broad peak in the inclusive spectra of the transferred energy. The width of the peak is a consequence of the Fermi motion of the nucleons inside the nucleus. Coincidence measurements (e,e′N) can give detailed information on the combined nucleon-hole energy and momentum distribution, the so-called spectral function in the target nucleus. The required minimal luminosities for different experiments are summarized in Table 2.

Table 2: Required luminosities for different studies. A spectrometer setup with 2π solid angle coverage is adopted. The values in square brackets indicate required luminosities when using a conventional spectrometer setup.

Reaction	Deduced quantity	Target nuclei	Luminosity/ $cm^{-2}s^{-1}$	
Elastic scattering at small q	Rms charge radius	Light	10^{26}	*[3 10^{26}]*
First minimum in elastic form-factor	Charge-density distribution with 2 parameters.	Light	10^{28}	*[10^{29}]*
		Medium	10^{26}	*[7 10^{26}]*
		Heavy	10^{24}	*[5 10^{24}]*
Second minimum in elastic form-factor	Charge-density distribution with 3 parameters.	Medium	10^{29}	*[10^{30}]*
		Heavy	10^{26}	*[8 10^{26}]*
Giant resonance	Strength, position, width, decay channels.	Medium and heavy	10^{28}	*[7 10^{28}]*
Quasi-elastic scattering	Momentum distribution, spectral function.	Light	10^{29}	*[2 10^{30}]*

1.2 Competitiveness

The necessity for an electron-exotic-nucleus scattering facility was also recognized in the concept of the future facility at RIKEN, Japan [11]. There similar attempts were made to incorporate the option of electron scattering of radioactive isotopes by means of multi-storage ring system (MUSES) The

achievable luminosities at the eA collider are highly favourable when compared with the MUSES project. The FAIR facility, based on pulsed beams from a synchrotron, is optimized for storage-ring operation whereas the RIKEN project relies on intense (quasi) DC beams from cyclotrons.

Table 3 shows, that the eA Collider experiments could even luminosity-wise become competitive to conventional fixed target experiments, due to the charged fragment detection scheme.

Table 3: Comparison of a sample inelastic scattering experiment: fixed target versus collider mode.

	Fixed target [12]:	**Approximate gain factor:**	**Collider:**
Reaction	^{48}Ca(e,e‘n)		^{48}Ca(e,e‘A‘)
Neutron solid angle	$\mathbf{\Omega_n} \approx$ 100msr	**100**	$\mathbf{\Omega_n} \approx 4\pi$
Detection efficiency	$n_{\mathbf{eff}} \approx$ 20 %	**5**	$n_{\mathbf{eff}} \approx$ 100 %
Electron scattering angle	$\mathbf{\Theta_{e'}}$ = 40 °	**50**	$\mathbf{\Theta_{e'}}$ = 5 °
Total gain		$>\mathbf{10^4}$	
Exp. luminosity	$\mathbf{L=10^{31} - 10^{32}}$ cm^{-2} s^{-1}	Required luminostity	$\mathbf{L \geq 10^{28}}$ cm^{-2} s^{-1}

A major advantage of the eA Collider is the possibility to fully analyze the ‘target nucleus’ after reaction as it is moving with the ion beam into the arcs of the storage ring that can be used as magnetic spectrometers. Summarizing, the most attractive as well as challenging features of the proposed concept are:

- The project represents a first attempt to implement electron scattering in studies of unstable exotic nuclei structure utilizing heavy-ion storage rings.
- The detector system under consideration allows to handle a wide class of different nuclear reactions and thus to address numerous physics questions. Kinematically complete measurements are feasible, quite in contrast to conventional electron scattering experiments.
- Technologically, the requirement of high resolution combined with high acceptance for the electron spectrometer and ultra high vacuum technology for fragment detectors is most demanding and requires non-standard solutions of the experimental setup design.

2 Experimental method and detector system

2.1 Experimental concept and requirements

The ELISe objectives consist of theory-assisted simulations of key experiments accompanied by the specific design of the relevant subsystems (luminosity monitor, electron spectrometer, in ring detection systems) of the eA-scattering experiment:

(1) The essential instrument is a Large Acceptance and High Resolution electron Spectrometer (LAHReS), which is needed to analyze the momenta and scattering angles of the scattered electrons. The required momentum resolution and angular resolution are 10^{-4} and 1 mrad, respectively. In addition, the spectrometer should allow to accurately localizing the reaction vertex inside the reaction zone. Existing magnetic spectrometers only partially fulfil these specifications, and in order to obtain a reasonable compromise for a novel design, simulations guided by specific theory input are to be performed.

(2) We foresee to implement (1) in two stages. We plan to perform test experiments at the TU-Darmstadt with a currently developed dispersive dipole stage in front of a magnetic spectrometer in order to study small angle scattering. Such a system could also be used in the storage ring in order to predeflect electrons out of the interaction zone towards a magnetic spectrometer without disturbing the circulating beam. The elastic scattering experiments at very low momentum transfer can already be performed with a very simple magnet setup that allows reconstructing the electron scattering angle only (small angle

spectrometer SAS). The SAS design should also facilitate the luminosity measurements which are necessary for the absolute cross section normalization.
(3) This stage would precede the final design and implementation of the Large-Angle and High-Resolution Electron Spectrometer (LAHReS). In addition, a fragment tracking system, to be operated in UHV and placed close to the interaction zone, needs to be developed.
(4) The detector system for the heavy fragments and ejectiles (neutrons and charged particles) is very similar, to most extent even identical to that describe in the EXL LoI [EXL04] to which we refer details.

2.2 The eA collider

The eA Collider consists of the NESR, which serves to store and cool the exotic nuclei and the electron-storage ring, both operated in collider mode. A conceptual design study of the eA collider is available [13] which is reflected in the GSI conceptual design report [CDR]. The basic parameters of the collider are listed in Table 4. The physics simulation work from this project will serve as input into further design studies.

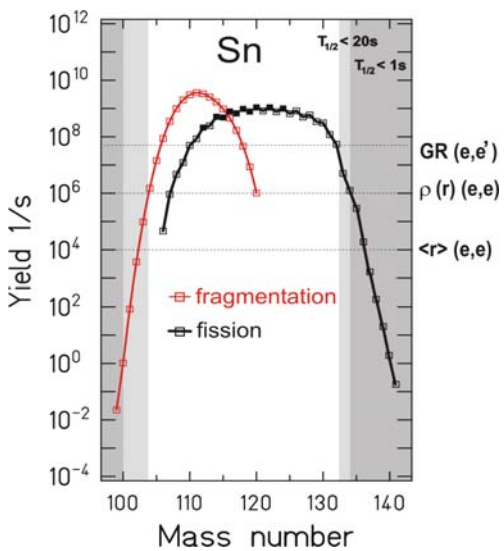
Table 4: Key parameters of the electron-heavy ion collider.

Parameters	Electron ring	Ion ring (NESR)
Circumference	45.215 m	187.717 m
Energy	200-500 MeV	200-740 MeV/u
Number of bunches	6-8	36-42
e^- / ions per bunch	5×10^{10}	$\sim10^{7}$

In the following, we will present examples for scattering experiments being feasible with current technology. However, we expect that new developments in cooling and spectrometer design will certainly extend the range of investigated nuclei even further towards the drip lines.
To a large extent, the maximum number of ions which can be accumulated in a single bunch of the NESR is limited only by space-charge effects. This results in a maximum luminosity of $L \approx 10^{29}$ $cm^{-2}sec^{-1}$ for an ion-beam energy of 740 MeV/u. The luminosity does not significantly depend on the electron energy E, within the range E = 200 to 500 MeV. However, it increases by about an order of magnitude with ion-beam energy increasing from E_I=200 MeV/u to 740 MeV/u).

Table 5: Number of ions per bunch and luminosity of the eA Collider for selected referenc nuclei. Production cross sections, separation efficiency and space-charge limits for stored beams are included. An illustration of envisaged experiments with Sn isotopes is shown in the figure.

Nucleus	Number of ions/bunch	Luminosity/ $cm^{-2}s^{-1}$
$^{238}U^{92+}$	0.9×10^{7}	1.0×10^{28}
$^{56}Ni^{28+}$	2.8×10^{7}	3.3×10^{28}
$^{69}Ni^{28+}$	2.8×10^{7}	2.4×10^{28}
$^{71}Ni^{28+}$	6.6×10^{6}	1.1×10^{27}
$^{104}Sn^{50+}$	6.0×10^{5}	7.0×10^{26}
$^{132}Sn^{50+}$	1.6×10^{7}	1.8×10^{28}
$^{133}Sn^{50+}$	2.1×10^{6}	1.8×10^{26}



The proposed eA Collider will be operated with contra-propagating (head-on collisions) electron-ion beams. The possibility of co-propagation (merging beams) may be considered in the future. In this mode, the spectral energy resolution could be improved into the low momentum transfer region, however, the size of the reaction zone is enlarged considerably.

The circumferences of the rings were designed such that, within one turn, about 40 NESR bunches collide with one of the eight bunches circulating in the electron ring. As previously mentioned, the maximum number of ions which can be accumulated in a single bunch of the NESR, and consequently, the maximum luminosity, is limited by space-charge effects, and therefore decreases from light to heavy bare ions. The expected number of radioactive ions per bunch and their corresponding luminosities are listed in Tab. 5 for a few reference nuclei. A detailed description of eA Collider parameters can be found in reference [13].

2.3 The electron spectrometer and focal plane detector

The resolution of the excitation energy for the colliding beams is determined by mainly two effects. (i) The electron energy in the center-of-mass system (cm) of contra-propagating beams is significantly larger then that in laboratory system, e.g., the cm energy for 740 MeV/u ion beam and 500 MeV electron beam energy is equal to about 1600 MeV. (ii) While in the fixed target experiment, the energy E′ of the elastically scattered electron (and thus ω) is independent of the scattering angle θ to a large extent, the dependence of E' on θ is very steep in a measurement with colliding beams.

This can be seen in Figure 4, where $E'(\theta)$ is shown for the different beam configurations. The variation in the energy is of outstanding importance for the construction of the electron spectrometer. Both of these kinematical effects result in special demands to the resolution of the electron spectrometer. To achieve an excitation energy resolution of about 500 keV, the momentum and angular resolution should be not worse than $\delta p/p \approx 10^{-4}$ and $\delta\theta \approx 1$ mrad, respectively.

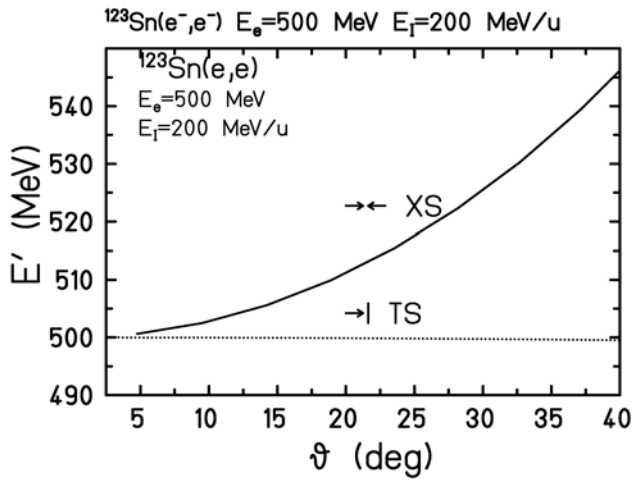


Figure 4.

Dependence of the scattered-electron energy on the scattering angle for fixed target experiments (→|), and counter-propagating beams (→←).

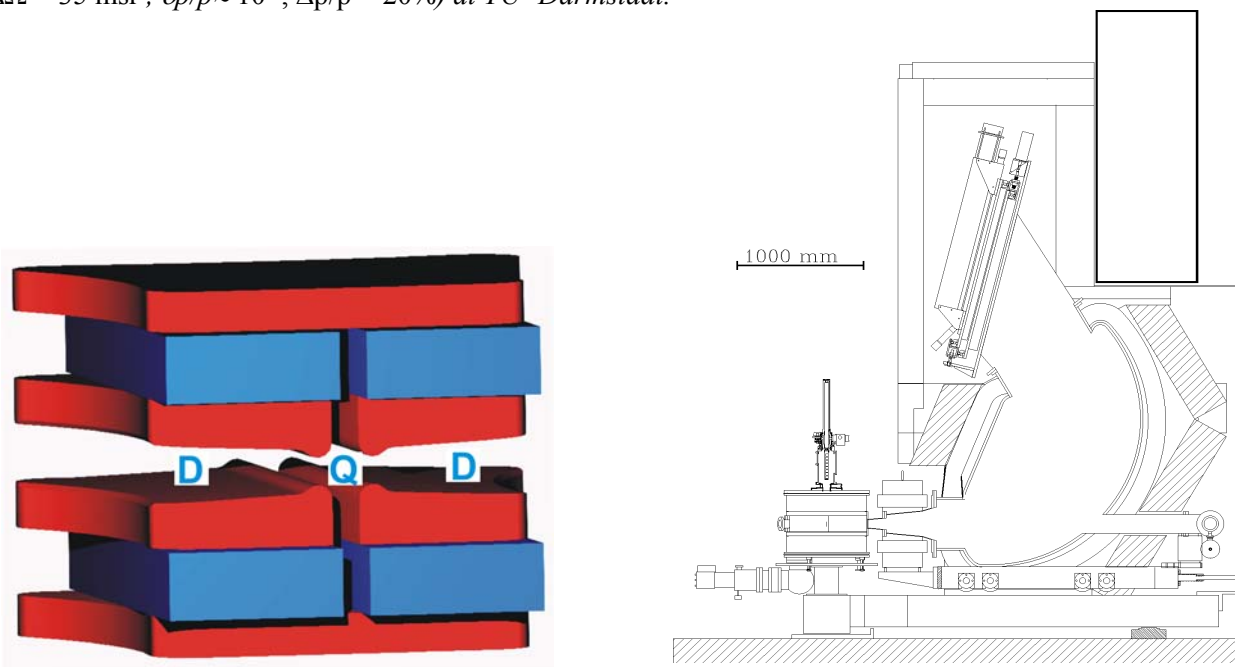
The technological challenge for the eA collider results from the simultaneous requirement for large acceptance and high momentum resolution. In addition, the spectrometer should allow tracking the position of the reaction vertex inside the reaction zone. Existing magnetic spectrometers only partially fulfil these specifications. For instance, the electron spectrometers at the universities of Darmstadt [14] and Mainz [15] and at the research centre TJNAF [16] meet the requirements with respect to momentum and angular resolution. They can handle reaction zone extending up to 10 cm, but have only a moderate acceptance of $\Delta\Omega < 40$ msr. Existing toroidal and solenoidal spectrometers, e.g. HADES [17], BLAST [18] and BELLE [19], that cover 2π in azimuthal angle, provide the required acceptance, but have only modest resolution. The main limitations for the resolution arise from energy and angular straggling of electrons in the tracking detectors. A large-acceptance spectrometer has advantages, but further research and development are needed for a suitable design, which can satisfy both above experimental requirements. Due to the fact that differential cross sections for electron scattering decrease rapidly with the angle of the scattered electron, an

ideal electron spectrometer should cover 2π in azimuthal angle but should require only a moderate acceptance in polar angle of about 10°-20°. A view of a typical high resolution electron spectrometer is given in Fig. 5. The existing electron spectrometer QCLAM (TU Darmstadt) is taken as example. The double focussing magnet spectrometer with a length of 3.5 m of the reference trajectory and a length of 46 cm of the focal plane provides the required resolutions of $\delta p/p \approx 10^{-4}$ and $\delta\theta \approx 1$ mrad while covering a solid angle of 35 msr and a momentum bite of Δp/p = 20% at a maximum electron energy of 250 MeV.

Following the discussions in several workshops and conferences where we presented this project we now tend to believe, that magnetic focussing spectrometers can be build [19] with an acceptance up to about 100 msr. This number is to be considered as an upper limit for a magnetic focusing device with reasonable cost. The tracking devices with a toroidal (HADES,CLAS) or solenoidal (BELLE) magnetic field may allow to cover 2π in the azimuthal direction, thus gaining a factor of about 10 in solid angle coverage compared to the focussing spectrometer, at mean scattering angles corresponding to momentum transfers above 0.2 fm^{-1}.

A possible view of a in ring predeflection system that can be used in conjunction with a magnetic spectrometer can be seen in Fig. 5, left and right side respectively. A prototype of such a system, which will be used in order to perform very small angle electron scattering experiments, is currently designed and will be set up at TU Darmstadt. It consists of a pre-deflection magnet as shown on the left hand side of Fig. 5 where two dipole stages will be realized and can be used to bend scattered electron further away before entering the spectrometer. This is necessary as the fringe fields of the magnetic spectrometers would cause unwanted beam deflections in front of the Faraday cup that is used to normalize the beam current. These requirements are similar to the need to avoid any perturbation of the circulation ion and electron beams in the storage rings.

Figure 5. View of the foreseen pre-deflection magnet-system (schematic, fits into the scattering chamber; following the ongoing design study) and the Quadrupole Clam Shell electron spectrometer ($\delta\theta$=1,5 mrad , ΔΩ = 35 msr , $\delta p/p \approx 10^{-4}$, Δp/p = 20%) at TU- Darmstadt.



The focal plane detector system for the scattered electrons should consist of three multiwire drift chambers and a trigger detector. Two drift chambers are placed in dispersive direction and one in vertical direction. A plastic scintillator is used as a trigger and possibly a large Cherenkov counter for background suppression. With the information of the drift chambers and detectors placed at the entrance window of the spectrometer complete track reconstruction is possible even in the case of a large size of the reaction zone.

Careful considerations have to be done to investigate the possibility to reach the required angular and momentum resolution with these spectrometers, including the associated ultra-thin electron detector developments.

2.4 Luminosity monitor

The envisaged small angle electron spectrometer (SAS) is supposed to be used as luminosity monitor (see above). The required resolution in this case is moderate. Here the fact is used that the elastic scattering cross section is close to the Mott cross section at very small momentum transfer, where $<r^2> q^2 \ll 1$. Another option is to look for the emitted bremsstrahlung under zero degree.

2.5 Heavy –ion spectrometer and particle detectors

For a kinematically complete measurement, the mass and charge of the heavy fragment and fission products need to be identified and its momentum to be determined. Likewise, the momenta of neutrons or charged particles emitted from the excited projectile need to be measured. The requirements and the design of both, of the heavy-ion spectrometer, which utilizes bending magnets of the storage ring, and of the particle detection are practically identical to that specified in the EXL Letter of Intent [EXL04]. We refer to [EXL04] for the specifications. It is actually foreseen to share the light-particle detector system in order to minimize costs.

2.6 Electronics, trigger, and data acquisition

In contemporary gamma spectroscopy setups, e.g. the MINIBALL or RISING setup, and in future readout schemes, e.g. for the HESR experiments, one follows an approach, that seems also well suited for colliding beam experiments. Here digitization of all electronic signals takes place whenever they appear in the detector systems, and the gathered information is immediately processed and buffered by FPGA, DSP and CPU based computation boards. These boards also define the grouping in different detector subsystems. The trigger selections can be performed on-line in the cross linked computation boards. Finally, only relevant and preprocessed information, marked with timestamps, is transferred and put together to events that will be written to mass-storage. The time stamp granularity is chosen fine enough to distinguish different physical events, while time measurements that require resolution better than nanoseconds are performed on the individual boards. In view of a joint NUSTAR data acquisition system, we intend to benefit from the developments that are currently started within e.g. the FOPI upgrade project, and the Future DAQ Joint Research Activity from the I^3HP Initiative of the 6th EU framework (2004-2006) for the CBM, PANDA and COMPASS experiments.

2.7 Physics performance

For the assumed spectrometer design the following considerations were taken into account. A large-acceptance spectrometer would have advantages, but further research and development are needed for a suitable design that can satisfy both experimental requirements. Due to the fact that differential cross sections for electron scattering decrease rapidly with the angle of the scattered electron, an ideal electron spectrometer should cover 2π in azimuthal angle but only requires a moderate acceptance in polar angle of about 10°-20°. Simulations were made under the assumption that a MAMI-A type spectrometer is used for elastic scattering measurements. Two energies, 740 MeV/u and 200 MeV/u, for a ^{132}Sn ion beam in the NESR have been considered. The result is shown in Fig. 6. The transferred-momentum region from $0.02\ GeV^2/c^2 < Q^2 < 0.2\ GeV^2/c^2$ can be covered by three settings of the spectrometer. The achievable resolution in excitation energy E^* depends on the ion energy and on the scattering angle of the detected electrons. At 740 MeV/u one obtains an energy resolution of $\Delta E^* \approx 1$ MeV (FWHM). The resolution can be improved to about 0.5 MeV for 200 MeV/u, however, the luminosity in the latter case decreases by about a factor of three in that case.

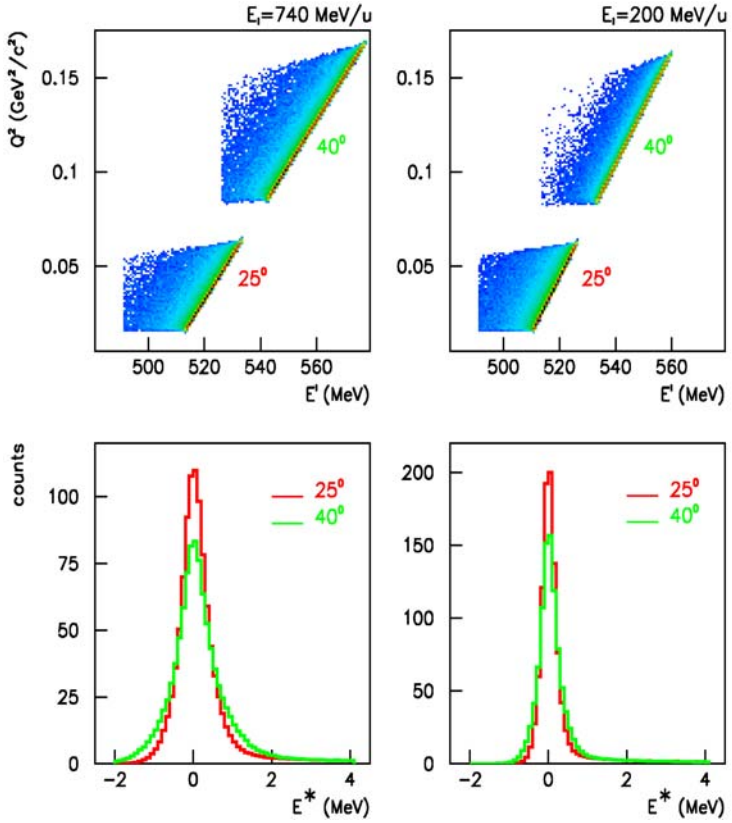


Figure 6.

Simulations of electron-nucleus scattering at ion energies in the NESR of 740 MeV/u (left) and 200 MeV/u (right). In the calculations, the ion optical parameters of the MAMI A electron spectrometer were used. The upper panel shows the square of the transferred momentum (Q) versus the energy of the scattered electrons (E′) the two groups of loci represent the acceptance of the MAMI A spectrometer, positioned at the laboratory angles 25° and 40°. The lower panel shows the resolution in excitation energy for the two angular settings, respectively.

2.8 Synergy with other LoI's

The NUSTAR Letter of Intent, aside from ELISe comprises subLoI's on external target [R3B04] and on light-ion storage ring experiments [EXL04], with evidently common interests as far as the physics goals are concerned. Both, from the common physics goals and similar development lines for specific detector subsets a close collaboration among the participants of R^3B, EXL and ELISe is most natural, and is manifested in the partial overlap in personnel. As already mentioned, for instance, the heavy-ion spectrometer and detectors for light ejectiles are essentially identical in case of EXL, pbar-ion scattering and ELISe. Atomic physics groups are also planning for a heavy-ion spectrometer serving a similar purpose and forming collaborations is envisaged. We rely on novel data acquisition schemes that are currently developed for the CBM, PANDA and Gamma-spectroscopy (e.g. AGATA, RISING, MINIBALL) setups. The integration and adaptation of the achievements is one of the tasks for the NUSTAR data acquisition groups within the ELISe, EXL, SuperFRS pbar-ion scattering and R^3B collaborations.

3 Implementation

3.1 Experimental area and radiation environment

The LARHeS and SAS apparatus needs to be installed at one of the four straight sections of the NESR. Since reaction rates are low for the ELISe type of experiments, no specific demands on radiation shielding beyond that needed for NESR operation seem to appear. Centered at the reaction zone, an area of 20 m × 20 m is requested. The height of the beam line above ground should be 2.5 m. Space for on-line data taking (~ 150 m²), laboratory and office space (~ 200 m²) to host the collaboration during experiments should be provided.

3.2 Cost estimate

The major investment within this project is the construction of the LAHReS electron spectrometer. The cost of such a device is estimated to be in the order of the investment costs for a MAMI A spectrometers, i.e. about 2-3 M€. The development costs including building the zero degree prototype detection system should not exceed 1 M€. Costs for detectors of the heavy-ion spectrometer, slow control, electronics, data acquisition and overheads are abut 500 k€ in accordance with the numbers given in the EXL proposal. The cost for the electron (and antiproton) storage ring, being part of the FAIR infrastructure, is estimated in the conceptual design report [CDR] to be 15 M€ (including the electron LINAC).

3.3 Organization and responsibilities

All of the research teams have experience with regard to scientific or technological aspects addressed in this LoI and will participate according to their expertise and physics interests. Some of the participating institutes have electron accelerators and modern electron spectrometers (MAMI at Institut für Kernphysik, Mainz and S-DALINAC at Technical University, Darmstadt), the experts from Budker Institut of Nuclear Physics, Novosibirsk, and Gesellschaft für Schwerionenforschung, Darmstadt are already actively involved in the design and construction of storage rings, electron cooling systems and, in particular, the eA Collider.

Table 6: Tasks and responsibilities.

Task	**Group**
Theoretical studies, support for the necessary simulation of the key experiments: - nuclear structure - astrophysics	BAS, CSIC, ESP, IPPE, UK
Simulation of specific experiments.	ESP, GSI, KI, UK
Simulation of electron spectrometer and general setup.	BAS, BINP, GSI, JINR, KI, LMU, RAS, TUD, UGM, UK
Fragment spectrometer: Design and construction. Research and development for the detectors capable to work at UHV conditions.	BINP, CTH, GSI, JINR, KI
Luminosity monitor. Design (and construction).	BAS, BINP, GSI, RAS, RIKEN
Electron spectrometer: Design (and construction). Test experiments	BAS, BINP, GSI, LMU, RAS, RIKEN, TUD, UK, WNSL
(Digital) readout electronics, trigger, DAQ, Slow control	CTH, GSI, UK

A Coordination Board (CB) will be formed out of representatives of the participating groups taking over major duties in developing the detector systems. At its next meeting, the CB will name the spokesperson and deputy of the ELISe collaboration. The main duties of the CB are to monitor the progress of the project and the quality of the developments, to ensure the reporting procedure according to the demands of the International facility at GSI as well as publication of results, and to guarantee optimal communication between the participants and thus economical usage of the provided funding. For the monitoring purpose, the CB will request internal reports from the participants at regular intervals.

To guarantee that various components of the project are properly dealt with, working groups are formed, which are responsible for the different parts and report to the CB. Responsibilities for the various tasks are given in Table 6 as agreed upon in collaboration meetings so far, but should be considered as tentative, a final decision will be taken after the CB has been formed. External expert advice will be asked for when deemed necessary by the CB.

The implementation of the ELISe spectrometer and ancillary components involves various steps, the general time line of the project is as follows: the implementation phase covers a period of 8 years (2004 – 2012). Study of in-ring fragment and neutron detector systems: (a) projectile fragment detector (mass and charge identification and momentum of heavy projectile fragment, ultra-high vacuum compatibility) and (b) neutron detectors (background, identification, momentum, energy, multiple-hit capability for out-of-ring detectors for projectile-rapidity neutrons) is supposed to be done at the end of 2005. The conceptual design of the detector system will be finalized end of 2006 (Technical design report). In ring magnet studies and tests; design and construction of a zero degree electron spectrometer should be done in the first half of 2007. The technical developments of the subtasks (e.g. detector prototypes, electronics and read-out schemes) and test measurements will be performed until end of 2007 and a technical report is delivered. It is intended to show the proof of principle of all subunits until 2010 and subsequently realize the full implementation of SAS and LAHReS system in 2012.

3.4. Beam time considerations

Based on the expected luminosities, a typical experiment requires about two weeks of beam. We estimate a total running time of 2 month per year. The effective beam request, however, will be lower since the storage mode needs beam from the synchrotrons only during the accumulation phases. It might be considered if other experiments in the storage ring can be operated in parallel.

References

1. G. Münzenberg and G. Schrieder, AIP Conf. Proc. Nucl. Phys. at Storage Rings, Eds. H.-O. Meyer and P. Schwandt, 293 (2000); L. Chulkov, G. Münzenberg, G.Schrieder, and H.Simon, Physica Scripta **T104,** 144 (2003)

2. R. Hofstadter, Rev. Mod. Phys. **28**, 214 (1956)

3. J. Friedrich, N. Voegler, R.-G. Reinhard, Nucl.Phys. **A 459**, 10 (1986)

4. H. de Vries, C.W.de Jager, C. de Vries, Atomic Data and Nucl. Data Tables **36,** 495 (1987)

5. R. Neugart, Euro Phys. Journ. **A 15**, 35 (2002); E.W. Otten, Treatise on Heavy Ion Science **8**, 517 (1989)

6. F. Touchard, J.M. Serre, S.B. Buettgenbach et al., Phys. Rev. **C 25,** 2756 (1982)

7. B.A. Brown, Phys. Rev. Lett. **85**, 5296 (2000); S. Typel, B. A. Brown, Phys. Rev. **C 64**, 027302 (2001)

8. G.J. Kramer, H.P. Blok, L. Lapikas, Nucl. Phys. **A 679**, 267 (2001)

9. V. R. Pandharipande, I. Sick, and P.K.A. deWitt Huberts, Rev. Mod. Phys. **69**, 981 (1997)

10. Th. Weber, R.D. Heil, U. Kneissl, W.Wilke, Th. Kihm, K.T. Knöpfle, H.J. Emrich, Nucl. Phys. **A 510**, 1 (1990)

11. T. Suda, K. Maruayama, Proposal for the RIKEN beam factory, RIKEN, 2001

12. S. Strauch, P. von Neumann-Cosel, C. Rangacharyulu, A. Richter, G. Schrieder, K. Schweda, and J. Wambach, Phys. Rev. Lett. **85**, 2913 (2000)

13. I.A. Koop, M.S. Korostelev, P.V. Logatchov, I.N. Nesterenko, A.V. Otboev, V.V Parkhomchuk, V.M. Pavlov, E.A. Prevedentsev, D.N. Shatilov, P.Yu. Shatunov, Yu.M. Shatunov, S.V. Shiyankov, A.N. Skrinsky, and A.A. Valishev, *Conceptual Design of an Electron-Nucleus Scattering Facility at GSI, Final Report.* (GSI internal Report)

14. J. Carter, H. Diesener, U. Helm, G. Herbert, V. Huck, P. v. Neumann-Cosel, C. Rangacharyulu, A. Richter, J. Ryckebusch, G.Schrieder, A. Stacheck, and A.Stiller, Phys. Rev Lett. **72,** 1994 (1994); H. Diesener, U. Helm, P. von Neumann-Cosel, A. Richter, G. Schrieder, A. Stacheck, A. Stiller, J. Carter, Nucl. Phys. **A696**, 272 (2001)

15. K.I. Blomqvist, W.U. Boeglin, R. Böhm, M. Distler, R. Edelhoff, J.Friedrich, R. Geiges, P. Jennewein, M. Kahrau, M. Korn, H. Kramer, K.W. Krygier, V. Kunde, A. Liesenfeld, H. Merkel, K. Merle, U. Müller, R. Neuhausen, E.A.J. M. Offermann, Th. Pospischil, A.W. Richter, G. Rosner, P. Sauer, S. Schardt,

H. Schmieden, A. Wagner, Th. Walcher, and S. Wolf,
Nucl. Instr. and Methods in Phys. Res. **A 403**, 263 (1998).

16. W. Brooks and CLAS Collaboration, Nucl. Phys. **A 663**, 1077 (2000).

17. J. Friese, for the HADES collaboration, Nucl. Phys. **A 654**, 1017c (1999).

18. The BLAST Collaboration, *Technical Design Report (1997)*, *http://blast.lns.mit.edu/BlastNotes/;*
R. Alarcon and BLAST Collaboration, Nucl. Phys. **A 663**, 1111 (2000).

19. The BELLE Collaboration, *KEK Progress Report 2000-4*, *http://beauty.bk.tsukuba.ac.jp/belle/nim/;*
Nucl. Inst. Meth. **A 479**, 117 (2002)

20. Rare Isotope Physics at Storage Rings, International Workshop, 2002, Hirschegg, Austria,
http://www-w2k.gsi.de/frs/meetings/hirschegg/program.asp; talks by I. Blomqvist, and S.Kato

Antiproton-Ion Collider: A tool for the measurement of neutron and proton rms radii of stable and radioactive nuclei.

April 7, 2004

Prologue

The main goal of the LOI is to provide for synergy between hadron and nuclear structure physics using antiprotons as probe for the study of neutron and proton distributions of exotic nuclei simultaneously. We propose to use for this purpose the electron ion collider modified such that antiprotons may be stored in the electron ring and brought to head on collisions with radioactive ion beams stored in the NESR. The products of the antiproton induced reactions with the exotic nuclei are proposed to be detected with similar methods as with reactions using internal targets in inverse kinematics. So synergy is also reached in the methodology. The proposed method is unique and promises also special nuclear structure information.

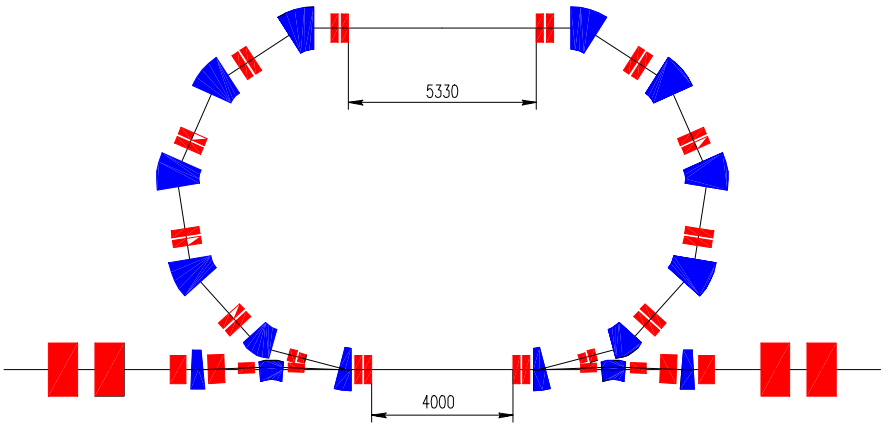


Figure of the proposed antiproton ion collider with a sketch of the collision zone in the lower part of the figure, which shows also a part of the magnetic lattice of the NESR in which the exotic ion beams circulate. The reaction products are detected in the NESR using Schottky spectroscopy or particle detection following a dispersive magnet section.

Abstract

An antiproton-ion collider is proposed to study antiproton absorption at medium energies in stable and radioactive, (favourably neutron rich) nuclei for a determination of both neutron and proton rms radii and their momentum distributions, respectively [1]. It is anticipated to make use of the electron ion collider complex [2] with appropriate modifications of the electron ring to store, cool and collide antiprotons of 30 MeV energy with 740A MeV ions in the NESR[3]. Furthermore a 30 MeV antiproton source has to be built either by constructing a transfer line from the RESR to the electron ring or using a small extra ring for accumulation and cooling of low energy antiprotons.
It has been shown that measurements of total and partial absorption
cross sections of antiprotons on the neutrons and protons of a nuclear target, respectively, are suitable to determine the rms radii of neutron and proton ground state density distributions in stable and radioactive nuclei [4]. An exclusive measurement of the recoil momentum distributions following the antiproton absorption on a neutron and a proton gives the momentum distributions of the absorbed neutron and proton respectively. For collisions of 740A MeV ions stored in the NESR and 30 MeV antiprotons, the kinematics is such that the recoil nuclei circulate in the ring acceptance and can be momentum analyzed and identified either by Schottky noise frequency spectroscopy or by particle identification using momentum analysis, time of flight, energy and energy loss measurement behind the first ring bending magnets at 45 degrees following the collision zone.
Whereas the physics basis of this LOI has been worked out theoretically [4] and is well understood, careful design and simulation work has to be put in to find an optimised lay out of the electron ion collider to make it suited for studies of antiproton ion collisions. Special care has to be taken for the design of the collision zone and a low energy electron cooler and RF for acceleration and bunching should be added. Yet everything looks such that no drastic changes have to be done to reach acceptable luminosities (~10^{23}) for antiproton ion collisions, especially in view of the large absorption cross sections (>1 barn) and the large detection efficiency (~100%) of the reaction products in inverse kinematics.

The figure shows a lay out of the magnetic lattice of the antiproton ring including the collision zone with the NESR ion ring. Note the 4 m long collision zone in which the ion beam stored in the NESR (lower lattice section) overlaps with the counter moving antiproton beam. In the straight section opposite to the collision zone, an electron cooler and a RF cavity can be installed. Both straight sections are dispersion free.

Members of the Collaboration

A collaboration has not yet been formed. Interest has been expressed by several groups, some of which are listed below. If this facility can be built, many users will be attracted, due to the interesting physics case. At this stage the collaboration with the Budger Institute for Nuclear Physics (BINP) group is most important for a final lay out of the collider including a technical design report and cost estimates.

Munich, Germany, Physik-Department TU München, P. Kienle, R. Krücken, K. Suzuki, J. Homolka, Th. Faestermann *et al.*

Novosibirsk, Russia, BINP, A.N. Skrinsky, Yu.M. Shatunov *et al.*

Giessen, Germany, Inst. f. theor. Physik, Uni. Giessen, H. Lenske,

Vienna, Austria, IMEP, J. Marton *et al.*

Tokyo, Japan, University of Tokyo, E. Widmann *et al.*

Darmstadt, Germany, GSI, B. Franzke, C. Kozhuharov *et al.*

Spokesperson:
Name: P.Kienle E-Mail:Paul.Kienle@ph.tum.de

1. Introduction and overview including the physics case.

A novel method is proposed to study neutron and proton distributions of stable and unstable nuclei, produced by projectile fragmentation, by studying medium energy antiproton absorption in a collider mode. A modified electron-ion collider [2] is used to store 30 MeV antiprotons transferred from the RESR or a dedicated small storage ring for low energy antiprotons and brought to head on collision with 740 A MeV ions stored in the NESR. Luminosities of about 10^{23} $cm^{-2}s^{-1}$ may be reached with 10^6 ions in the NESR both in bunched and coasting mode of operation. As the antiproton absorption cross sections are expected to be in the order of a barn or more, reaction rates of ~ 6-10 per min will allow accurate measurements of the absorption cross sections. Even with a smaller number of ions measurements seem to become feasible. But a detailed design and simulation study is needed for such an antiproton ion collider to reach optimised performance. The reaction kinematics is such that products following the antiproton absorption are focused in forward direction. They can be detected with high efficiency by arrays of position sensitive Si detectors in a dispersive plane of the NESR behind the collision zone. This allows the measurement of exclusive absorption cross sections on the neutrons and protons of the circulating ions simultaneously. From these cross sections one may readily derive rms radii with reliable reaction models for the neutron and proton distributions with unattained precision. Furthermore one can measure with such a set up the momentum distributions of the recoils following the annihilation of a neutron and a proton, which yields their respective momentum distributions. An even more elegant method is based on Schottky noise frequency spectroscopy. In coasting mode operation one can identify all absorption products by Schottky noise frequency spectroscopy and determine their production cross sections. This opens most likely an easier way to measure rms radii of the neutron and proton distributions of exotic nuclei simultaneously. But it is also possible to detect a single ion by resonant Schottky probes and measure its revolution frequency and thus its momentum in short times (ms). The effect of the cooling on the reaction products may be reduced by switching the cooler voltage or introducing some dispersion in the cooling zone. Furthermore the cooling action can be studied by recording the time behaviour of the Schottky spectra which are recorded successively. Thus we have a non destructive way to measure the momentum distributions of the nuclei following annihilation of protons and neutrons. Furthermore the total cross section may be measured by the observation of the decrease of the coasting primary beam as function of time.

2. Detector Subsystems

The detectors of the recoils consists of arrays with several layers of double sided Si-strip detectors, mounted in a metal box with a thin metallic entrance window. They are inserted in the UHV chamber of the NESR at the first dispersion plane of the magnetic lattice following the collision zone from both sides of the ring. The detector positions will be adjusted with high precision that they are hit by reaction products only, which are bent out of the primary beam orbit. The detector system will have complete particle identification and momentum measuring capability. Such a system has been used in the ESR and is under further test and development; similar systems are also needed for the proposed research within the Letters of Intent submitted by the EXL, ILIMA, and ELISe collaborations. For Schottky spectroscopy standard time capture techniques are suitable. Fast resonant pickups will be developed also for the mass measurements.

3. Trigger and Data Acquisition

Standard data acquisition and Schottky time capture (TCAP) acquisition systems will be available.

4. Physics Performance

The decrease of the ion current can be used as a luminosity monitor, which allows to measure the partial neutron and proton annihilation cross section as fraction of the total cross section derived from time behaviour of the current. The momentum spectra can be calibrated with the measured total energies in the detector array.

5. Implementation

5.1 Experimental Area

The antiproton ion collider is situated in the same area as the electron ion collider. In fact they are identical. In addition one needs space for a low energy antiproton transfer line from the RESR to the antiproton collider ring or from an other low energy antiproton storage ring.

5.2 Radiation Environment

The experiments produce low reaction rates, so no special radiation problem should come up.

5..3 Cost Estimates

Additional costs arise from the antiproton transport system, a cooling system and a RF system for the antiproton collider ring. Its cost must be estimated by the machine group. Furthermore one needs electron cooling in the RESR at intermediate energies or an additional small antiproton storage ring.

5.4 Organisation and Responsibilities

The responsibilities for the operation of the collider should be at the Facility for Antiproton and Ion Research (FAIR). Its core part consists of the NESR and the electron ring, modified such that it can be used as an antiproton storage ring. The latter could be well built by the BINP in Novosibirsk. The detector system is built and taken care of by experimental groups. A collaboration with a standard structure should be formed as soon as a positive response is available.

5..5 Time Schedule

The antiproton ring of the collider could be built after the NESR.

References:

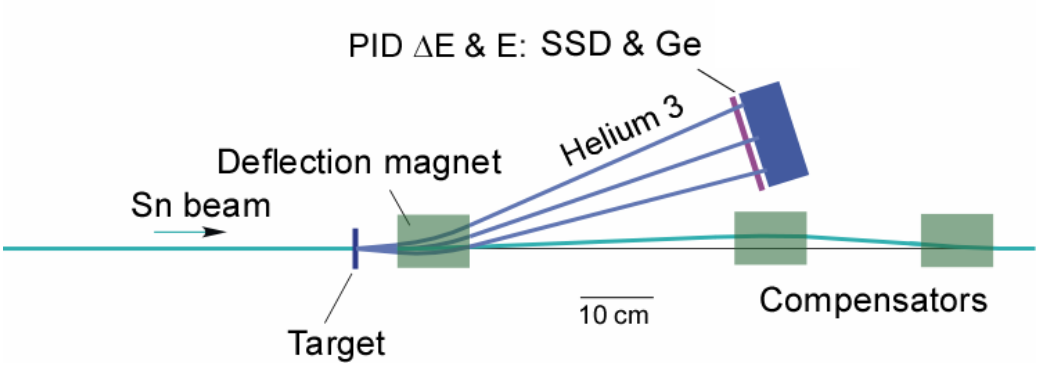
[1] P. Kienle, Nucl. Instr. Meth. B 214 (2004) 191.
[2] I.A. Koop et al.,Proc. EPAC 2002, Paris p. 620.
[3] A.N. Skrinsky, private communication
[4] H. Lenske and P. Kienle, to be published

Spectroscopy of Pionic Atoms with Unstable Nuclei

April 8, 2004

Abstract

We propose an experiment to perform spectroscopy of pionic atoms with unstable nuclei (RI) by using the $d(\mathrm{RI},{}^3\mathrm{He})\mathrm{RI}^*\otimes\pi^-$ nuclear reaction. The experiment is intended to be performed at the FAIR facility with an incident RI beam energy of 250 MeV/u.



Experimental setup in the NESR.

Collaboration

Kenta Itahashi[1], Masahiko Iwasaki, Haruhiko Outa,
Advanced Meson Science Laboratory, RIKEN, 2-1 Hirosawa, Wako-shi, 351-0198 Saitama, Japan,

Hans Geissel, Gottfried Münzenberg, Helmut Weick[2],
Gesellschaft für Schwerionenforschung, Planckstraße 1, D-64291 Darmstadt, Germany,

Kenji Gomikawa, Ryugo S. Hayano[3], Miki Shindo, Eberhard Widmann,
Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, 113-0033 Tokyo, Japan,

Karl Lindberg, Per-Erik Tegner[4], Irina Zartova,
Department of Physics, Stockholm University, AlbaNova University Centre, SE-10691 Stockholm, Sweden,

Albrecht Gillitzer,
Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany,

Ken Suzuki,
Physik-Department, Technische Universität München, D-85748 Garching, Germany,

Agnieszka Trzcínska,
Heavy Ion Laboratory, Warsaw University, ul. Pasteura 5a, 02-093 Warszawa, Poland,

Satoru Hirenzaki,
Department of Physics, Nara Women's University, Kita-Uoya Nishimachi, 630-8506 Nara, Japan,

Paul Kienle
Institute for Medium Energy Physics of the Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria,

Toshimitsu Yamazaki
RI Beam Science Laboratory, RIKEN, 2-1 Hirosawa, Wako-shi, 351-0198 Saitama, Japan.

[1] Spokesperson: itahashi@riken.jp
[2] Local contact: h.weick@gsi.de
[3] Co-spokesperson: hayano@phys.s.u-tokyo.ac.jp
[4] Co-spokesperson: tegner@physto.se

1. Physics Goals

The purpose of the experiment is to perform spectroscopy of pionic atoms with unstable nuclei (RI). The experiment is realized by employing new method of producing pionic atoms in inverse kinematics reactions $d(\mathrm{RI},{}^3\mathrm{He})\mathrm{RI}^*\otimes\pi$ and this method will lead us to extend the field of study to the pionic atoms with unstable nuclei. The experiment needs well developed equipment and will be feasible only in the new international accelerator facility at GSI.

The study of deeply bound pionic atoms has been developing after we established a method of spectroscopy by using nuclear reactions. There, pionic atoms are directly produced in a zero-momentum transfer (d,^{3}He) reaction and the Q–value of the reaction is measured to determine the mass of the reaction product. After improvements, we came to achieve the resolution of ~400 keV (FWHM). This method has extended the research region from the X–ray measurements of shallowly bound states to direct population and measurement of deeply bound states, for instance, 1s pionic lead and tin atoms. This has brought strong impacts [1–4] into various fields of today's physics [5,6].

In these deeply bound pionic atoms, the real pion is bound in extremely close vicinity to the nucleus and it even is partly buried in the nucleus. Performing spectroscopy, we have deduced the density dependent part of the strong interaction between a pion and a nucleus [7]. Also, the data are analyzed from the viewpoint of pion mass modification and chiral symmetry restoration of the “vacuum” in the nucleus, which is treated as zero-temperature high density matter stable in the laboratory. We have established evidence of the symmetry restoration and the magnitude of the restoration is estimated [1].

So far, the study of pionic atoms has worked as a very powerful tool. However, there is still a strong limitation. The target nuclei have to be β–stable. Here, we propose a further advanced method of nuclear reaction spectroscopy by using inverse kinematics [8] as described below. In order to fully understand the nature of the π-nucleus strong interaction, systematic studies of pionic atoms with a very wide range of nuclei are essential. Pionic states are sensitive to the structure of the nuclear surface, and their spectroscopy will serve as an opportunity to investigate the property of unstable nuclei using the pion as a sensitive probe. Figure 1 shows the calculated binding energy and width of a 1s state in a pionic tin atom when changing the neutron density distribution parameters, radial (c) and diffuseness (a) parameters. Precise measurements of pionic states will provide information on the properties of unstable nuclei. In inverse kinematics reactions, the emitted ^{3}He will have a small kinetic energy of about 60 MeV. This will help to achieve higher resolution.

There are clear reasons for proposing the experiment for the new facility at GSI. The new facility will provide the world’s highest quality beam of unstable nuclei. The produced beam will be stored in the storage rings. Since the proposed experiment requires a high luminosity and small emittance beam, any other facilities in the world does not fulfill the requirement. Hereafter, we will investigate the experimental feasibility of pionic atom spectroscopy with ^{132}Sn.

2. Experimental Principle

In our present spectroscopy, the pion is produced in a reaction and is bound to a nucleus. The elementary reaction is $n+d\rightarrow{}^3\mathrm{He}+\pi$, thus a neutron is separated from the nucleus simultaneously. The absolute coupling strengths with the neutron states depend on the magnitude of the overlap between the pion and the neutron wave functions. We measure the Q–value of the reaction (Q) near the π–emission threshold and the binding energy (B_π) is deduced according to

$$Q = m_{\pi^-}c^2 - B_\pi + S_\mathrm{n} - (M_\mathrm{d} + M_\mathrm{n} - \mathrm{M}_{3\mathrm{He}})\,c^2$$

where S_n is the neutron separation energy, $m_{\pi-}$, $M_d + M_n - M_{3He}$, respectively, denote the mass of the pion, deuteron, neutron, and ^{3}He, respectively. We expect to measure the bound state as a peak in the Q–value spectrum. Since the reaction in the center-of-mass frame is the same for inverse kinematics and normal kinematics important experience from the previous measurements is still valid for the proposed experiment. The pionic atom formation cross section for the experiment has been calculated by Umemoto *et al.* [8] and the ambiguity in the calculation is known to be small.

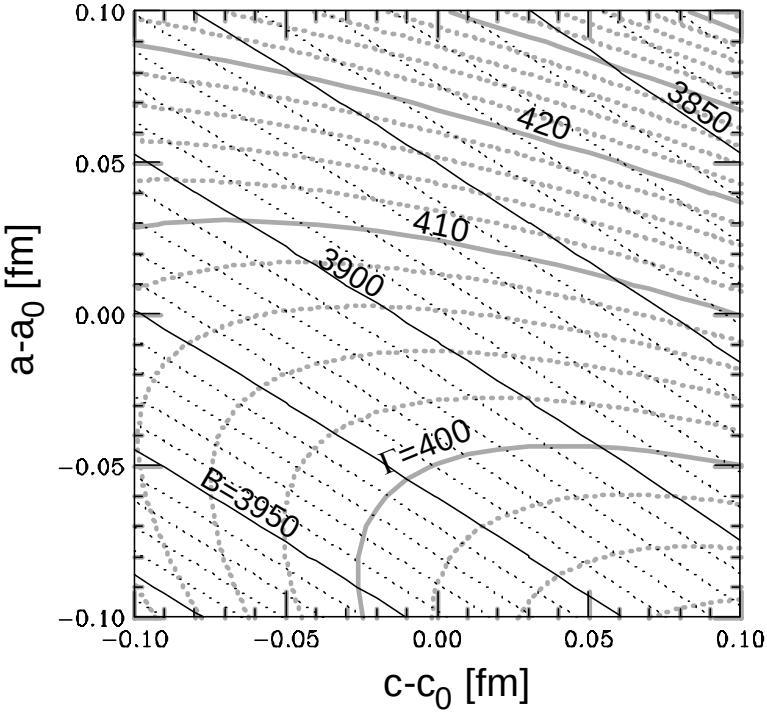


Fig. 1: Calculated binding energy and width in keV of the 1s state in a pionic tin atom (^{115}Sn) when changing the neutron density distribution parameters. The distribution used in the calculation is a two parameter Fermi model,
$\rho(r) = \rho_0/(1+\exp[(r-c)/a])$, where c_0=5.473 fm and a_0=0.552 fm.

In order to enhance the formation probability of pionic atoms and to suppress the quasi-free pion production, the momentum transfer of the reaction should be small. We have to choose the incident energy to ensure the recoilless kinematical condition for the pion relative to the target nucleus. Figure 2 depicts the momentum transfer dependency on the incident beam energy in case of the Sn(d,^{3}He) reaction for pionic atom formation. The incident beam energy of ~250 MeV/u is naturally selected for this purpose and this is valid also in the case of inverse kinematics.

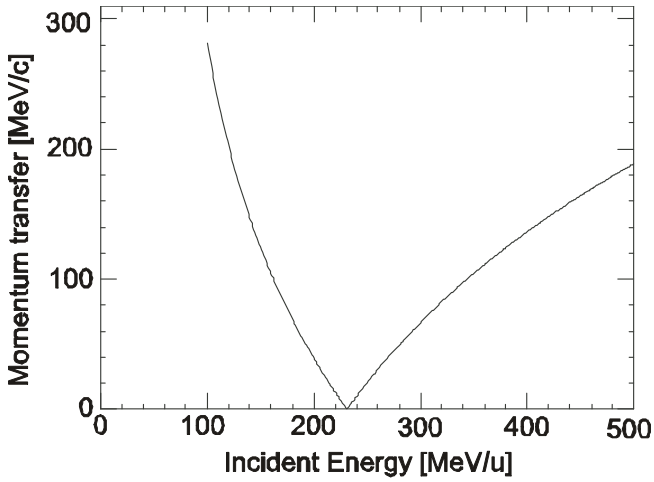


Fig. 2: Recoil momentum vs. incident energy in case of the (d,^{3}He) reaction. The recoilless kinematical condition is fulfilled near 250 MeV/u incident energy.

A difference related to the kinematical conditions appears in the ^{3}He emission angle dependence of the *Q*–value. Figure 3 shows a contour for a certain *Q*–value with both kinematics in the plane of parallel and transverse momentum in the laboratory frame. The emission angle in the center-of-mass frame (CM) is shown by small ticks for 0, ±45, ±90, ±135, 180 degrees. While the *Q*–value in the normal kinematics does not depend strongly on the ^{3}He emission angle, in the inverse kinematics the *Q*–value depends on both the kinetic energy of the ^{3}He and the emission angle. Thus, we need to measure both of them to achieve high resolution.

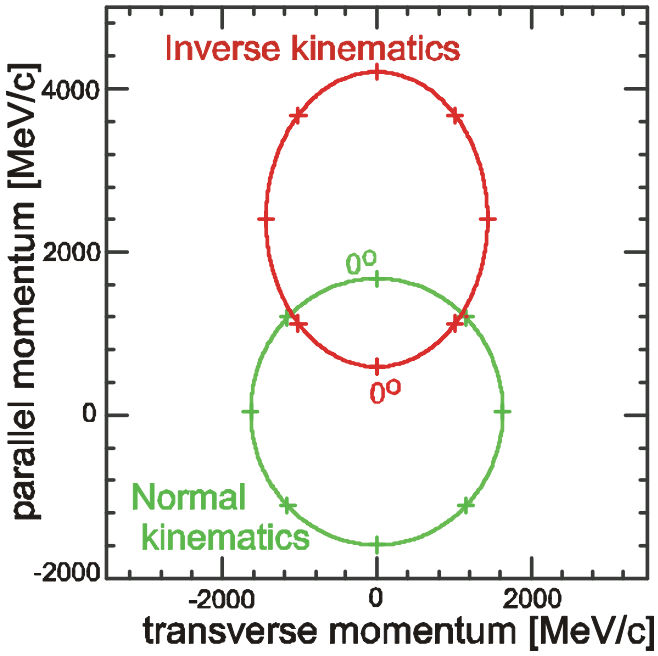


Fig. 3: A Q-value contour plot in the plane of parallel and transverse momenta in the laboratory frame.

3. Experimental Setup

In order to take advantage of the inverse kinematics, the present experiment needs to be performed at a storage ring. Here, to design the experiment in a realistic way, we have taken into account the specifications of the new facilities, SIS-100 and NESR. The ^{132}Sn beam is produced at the primary target at the entrance of the Super-FRS facility by either projectile fragmentation or an in-flight fission reaction and separated from other nuclei. The produced ^{132}Sn beam is guided to the CR-NESR facility, the momentum spread is reduced by cooling and the ions are decelerated to 250 MeV/u in the RESR. The beam intensity in the NESR by one injection is assumed to be ~5×10^7 and for higher yield, we also consider multiple injection to increase the intensity. The repetition cycle is assumed to be 5 seconds including the cooling time.

As for the target, we are thinking about a 1 mm wide, 1 μm thick strip of solid lithium deuteride (LiD). A LiD target has a clear advantage in its thickness. We can reach a sufficient yield with a low intensity beam. Calculations show that the lithium of LiD does not cause severe ^{3}He background in the region of interest as a tail of the fragmentation reaction, but we still need further investigations. The energy loss in the target may lead to a severe problem of temperature increase in the target. The total heat deposit in the target amounts to 0.1 J (with 5×10^7 tin beam), which results in a temperature increase of about 1000 Kelvin at maximum. The heat deposit depends also on the effective beam intensity which hits the target. We are thinking about widening the beam at the target to have lower effective intensity with longer beam life in the ring. We still need further investigations of this matter.

Figure 4 shows the present design of the experimental apparatus. We measure the Q–value by measuring the emission angle and the kinetic energy of the ^{3}He. Since the formation cross section has a peak in forward direction, the detector system was designed to have its acceptance accordingly. In the reaction of $d(^{133}\mathrm{Sn},^3\mathrm{He})^{132}\,\mathrm{Sn}\otimes\pi^-$, the emitted ^{3}He has a kinetic energy of about 60 MeV and this corresponds to about six times smaller rigidity than that of the stored RI beam. The ^{3}He is first separated from the beam by a deflection magnet. This deflection of the beam is compensated by two following magnets.

We place the main detectors of a silicon strip detector (SSD) and a planer Germanium detector at about one meter from the target. The SSD is 300 μm thick and has 3 × 3 cm^2 effective area with 640 + 640 strips on both sides. The emission angle of the ^{3}He is measured as the position on the SSD. The position resolution is about 50 μm (FWHM) and is sufficient. The energy loss in the SSD is also measured. The total energy of the ^{3}He is measured by the 2 cm thick Germanium detector.

The small amount of material still causes deterioration of the resolution due to energy straggling. Thus, to have the best resolution, the detector system should be located in the ultra high vacuum of the storage ring without any separating foil. We need to develop SSD and Germanium detectors to be operated in such high vacuum. Table 1 summarizes the estimated Q–value resolution and the contributions. The estimated resolution is 250 keV (FWHM). The largest contribution is the resolution of the Germanium detector, the others are very small.

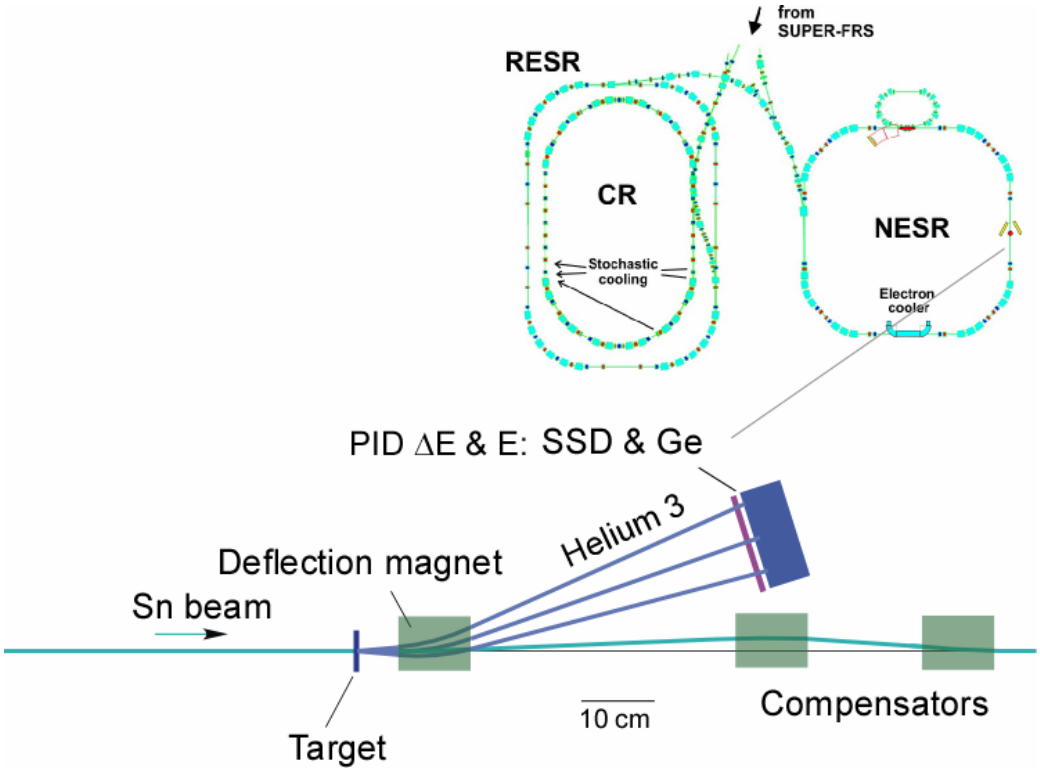


Fig. 4: Experimental setup in the NESR

As summarized in the Table 1, the estimated *Q*–value resolution is higher than the presently achieved value of 400 keV. We are preparing for the same type of experiment with stable nuclei in the existing facility to achieve this highest resolution. This experiment will serve as a precious opportunity to gain experience for the proposed experiment.

Energy loss in the LiD target	25 keV
Multiple scattering in the target and angular resolution	12 keV
Energy resolution of SSD	75 keV
Energy loss straggling in the dead layer of SSD	50 keV
Germanium detector energy resolution	225 keV
Q–value resolution	240 keV (FWHM)

Table 1: Q–value resolution.

An area of 3 m along the beam line and 2 m in transverse direction is required as experimental space around the target and in addition room for the power supply of the magnet and the cooling system for the Germanium detectors. The rooms for electronics and data acquisition can be shared with EXL.

4. Yield and Cost Estimation

The experimental yield is estimated and tabulated in Table 2.

Beam	^{133}Sn 250 MeV/u
Intensity	5×10^7/injection
Circulation frequency	2 MHz
Life time	18 ms
Repetition	5 sec
Cross section	25 μbarn/sr
Target	LiD 1 μm = 5.9×10^{18}/cm^2
Detector solid angle	900 μSr
Yield	170/hour

Table 2: Estimated yield.

The estimated costs including R&D are tabulated in Table 3.

	unit price	No.	total [euro]
Detector			180,000
Germanium	40,000	1	40,000
SSD	60,000	1	60,000
LiD target	3,000	5	15,000
Magnets	15,000	3	45,000
Vacuum	80,000	1	80,000
Electronics			40,000
Transportation			60,000
Total			340,000

Table 3: Estimated costs.

References

[1] K. Suzuki *et al.*, Phys. Rev. Lett. **92**, 72302 (2004).
[2] W. Weise, Nucl. Phys. A **690**, 98 (2001).
[3] Y. Akaishi and T. Yamazaki, Phys. Rev. C **65**, 044005 (2002).
[4] M. Iwasaki, *et al.*, nucl-ex 0310018 (2003).
[5] T. Yamazaki *et al.*, Z. Phys. A **355**, 219 (1996).
[6] H. Geissel *et al.*, Phys. Rev. Lett. **88**, 122301 (2002).
[7] Y. Umemoto *et al.*, Nucl. Phys. A **679** (2001) 549.
[8] T. Yamazaki *et al.*, Nucl. Inst. Meth. in Phys. Res. **A292** (1990) 619.