The RISING Project

Letter of Intent

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On behalf of the RISING Steering Committee representing the RISING collaboration

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Gamma-Spectroscopy with RISING at the FRS

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1. Introduction

It is proposed to use Euroball Ge-detectors for experimental campaigns at the GSI facility starting in 2003 to exploit unique opportunities for nuclear structure studies. Following a workshop held on November 23 - 24,2000 at GSI, the RISING (**R**are **I**sotope **S**pectroscopic **IN**vestigation at **G**SI) collaboration has been initiated to pursue this project. A list of the 34 collaborating institutions is given in appendix A

The SIS/FRS facility at GSI provides challenging new possibilities: by fragmentation or fission of relativistic heavy ions several hundred unstable rare isotopes can be generated with sufficient intensity for in-beam gamma-ray spectroscopy for the first time. Secondary beams can even be produced in high spin isomeric states. The beams can be used either at i) high energies (~100 MeV/u) for relativistic Coulomb excitation and fragmentation reactions, ii) slowed down to Coulomb barrier energies, enabling fusion, multiple Coulomb excitation and direct reactions or iii) stopped for decay studies. In three workshops held on March 9 at Göttingen, April 2-3 at Legnaro and April 6 at GSI the nuclear structure physics addressable in these domains has been discussed in some detail. This letter of intent summarizes the proposed physics and the intended experimental technique of the RISING project.

2. Types of Experiments

Three classes of experiments with specific technical requirements are envisioned with radioactive ion beams (RIB) at the FRS.

Fast beams around 100 A MeV

are used for relativistic *Coulex*, *nucleon removal* and *secondary fragmentation* experiments. The latter may lead to rather high angular momentum states. As special application they allow *g-factor measurements* for short lived (ps) states and systematic studies of the *spin alignment/polarisation* of RIB's.

Slow beams at 4 - 20 A MeV

due to large cross sections can be favourably used for *multiple Coulex* and *transfer reaction* experiments to measure single particle *spectroscopic factors* and *particle (hole) - particle (hole) effective interactions* near exotic doubly magic nuclei. Due to the low luminosity *deep inelastic* collisions and *fusion-evaporation* reactions may be exploited only in selected cases.

Stopped beams with-intensities ≤ 1/s

“on-beam” experiments of the radioactive species, such as *β-decay*, *isomer γ-spectroscopy* and the measurements of *half-lives in the ps -- ns range* and *nuclear moments*.

3. Physics of RISING

As a result of the series of workshops aiming at experiments with fast, stopped and slowed - down beams, under the constraints imposed by the intensity and optical quality of the radioactive ion beams, the nuclear structure topics to be studied at RISING are summarised in the following. More elaborate descriptions of the various experimental ideas, references and feasibility considerations can be found in individual project descriptions as attached in appendix B.

Shell structure

At N=Z the doubly magic nuclei ^{56}Ni and ^{100}Sn provide an excellent testing ground for single particle shell structure, proton-neutron interaction and the role of correlations, which are not treated routinely in mean field calculations (2a). On the other hand, the interaction used in large scale shell model calculations includes all correlations, but needs to adjust the monopole term to experimental data. The quadrupole (shape) and spin response near the ls-open shell closures, and the pairing (T=1 and T=0) by the cooperative interaction of protons and neutrons in identical orbitals (3h) pose a major challenge to shell model, microscopic-macroscopic and mean field theory. Both nuclei are predicted to have only about 60% of the closed shell configuration in their ground state wave function, the rest being up to 8p-8h excitations. At N>>Z the persistence of shell strength, melting of Woods-Saxon shell gaps and enforcement of harmonic oscillator (sub)shells are of prime interest (1a, 1b, 2d). The predictive power of mean field calculations is hampered by the poor knowledge of the isovector part of the interaction, which can be determined only by data at extreme N-Z. Experimental efforts concentrate on nuclei close to a line defined by ^{36}S, ^{48}Ca, ^{78}Ni and ^{132}Sn (3a, 3e).

Shape coexistence

The phenomenon of shape coexistence is caused by various structure effects, which can be traced back to the polarisation by high spin intruder orbitals, which happens to occur primarily in exotic regions of the Segré chart. At N~Z from ^{56}Ni to ^{100}Sn with the filling of the p,f,g orbitals the shape changes from spherical to triaxial, oblate, prolate, and is expected to return to triaxiality and finally sphericity (1d, 3d). Abrupt changes are due to deformed shell gaps opened by the strong proton-neutron interaction in identical orbitals. Along semi magic isotopic and isotonic chains midshell between shell closures 2p-2h and 4p-4h excitations across the shell gap into high-spin orbitals cause coexistence of spherical, oblate and prolate shape (2f) as seen in the Sn (Z=50) and Pb (Z=82) isotopes, so far without firm experimental assignment of the specific shape. Aided by shell gap melting, even the ground state may become deformed as in the well known N=20 nucleus ^{32}Mg (1e). Finally, high-K isomers, built by multi-quasi particle configurations, due to their influence on the amount of pairing and/or collectivity left, may give rise to shape changes (2c). Again the doubly “K-magic” nuclei with Z,N=72 and N=116 are extremely neutron-deficient resp. –rich (1g, 2d).

Symmetries

At N=Z mirror symmetry can be studied in isobaric analogue states (1c). Only for small T distortions as manifest in Coulomb energy differences (CED) have been developed into a spectroscopic tool recently. Large T mirror pairs of nuclei provide an alternative access to the isovector mean field interaction. Isospin mixing, which increases proportional to Z, can be studied in Fermi decay of T_z=0 odd-odd nuclei (2a). Structural and dynamical symmetries of the nuclear many-body system, subject to symmetries imposed by the nuclear forces, are observed in selected parts of the Segré chart only, depending on the underlying microscopic shell structure. A full mapping of the limiting symmetries U(5) (vibrator), O(6) (triaxial), SU(3) (axial symmetric) and the recently established transitional symmetries (2e, 3c), representing new paradigms of nuclear structure, require studies of low-lying states in neutron-rich nuclei (2e).

Collective modes

At N>>Z the shell gap melting is strongly related to the dilute neutron density and the decoupling of proton and neutron motion, which may give rise to a new low-lying E1 mode (Pygmy resonance). Along with the higher lying isovector GDR this provides access to the effective in-medium NN-interaction and the RMS charge radius at extreme N-Z (1h). The concept of a rotating octupole has been very successful in explaining the band structure of actinides, with little firm evidence so far on the static or dynamic character of the octupole correlations. More direct measurements of the E3 moment would give more insight in the underlying nuclear shape (3b).

4. Experimental methods

The experimental signature for nuclear structure is mainly taken from level energies, B(E2) and B(E3) values, magnetic moments and spectroscopic factors. The latter are barely known for exotic shell closures. Single particle intruder, T=1 seniority and proton-neutron spin-gap isomers provide excellent probes for spherical shell structure and residual interaction. Therefore experiments in the different campaigns focus on the following experimental methods and techniques.

Fast RIB around 100 A MeV

- Secondary fragmentation (1e);
- Nucleon removal;
- Relativistic Coulomb excitation (RCE) (1b), with isomer and/or particle decay tagging (1g);
- Differential recoil distance Doppler shift (RDDS) lifetime measurements (1e);
- GDR gamma-decay studies (1h);
- Spin rotation in transient magnetic fields (1f).

Stopped RIB

- α- and β-decay;
- γ-isomer decay;
- Electronic timing in the ps - ns range (2d);
- Spin rotation in external magnetic fields and electric field gradients (2b).

Slow RIB at 5-20 A MeV

- Single- and two-nucleon transfer (3g);
- Multiple Coulomb excitation (MCE) (3b);
- Coulex RDDS (3c);
- Fusion and deep inelastic reactions (3h)

5. Experimental Technique

The proposed gamma-ray spectroscopy of RIBs will be performed after in-flight isotope separation. It is planned to use 15 Cluster and 26 Clover detectors of the present EUROBALL IV array. These need to be arranged in different, newly designed set-ups fit to the respective RIB velocity.

The nuclei of interest will be produced in fragmentation of stable primary beams or projectile fission of ^{238}U at relativistic energies impinging on a ^{9}Be or ^{208}Pb target, which is located at the entrance of the GSI projectile fragment separator FRS. An average beam intensity from the SIS heavy-ion synchrotron between 10^9 medium heavy ions (e.g. ^{129}Xe)and 10^8 ^{208}Pb, ^{238}U per second can be expected. The FRS will be operated in a standard achromatic mode, which allows a separation of fragments by combining magnetic analysis with energy loss in matter. The separated ions will be identified event-by-event with respect to the mass and atomic number (A,Z) via combined time-of-flight, position tracking, and energy loss measurements. The standard detector set-up to identify and track ions from the FRS is shown schematically in figure 1 and will be used for all three experimental campaigns. At the intermediate focal plane, upstream from the degrader, a plastic scintillator is mounted. This serves for both time-of-flight (TOF) and position measurements. A set of detectors at the final focus consists of:

- two multi-wire proportional chambers (MW1,MW2), yielding horizontal and vertical positions,
- a four-fold ionisation chamber (MUSIC) providing energy-loss information ΔE,
- a plastic scintillator (SC2) which delivers the second TOF signal.

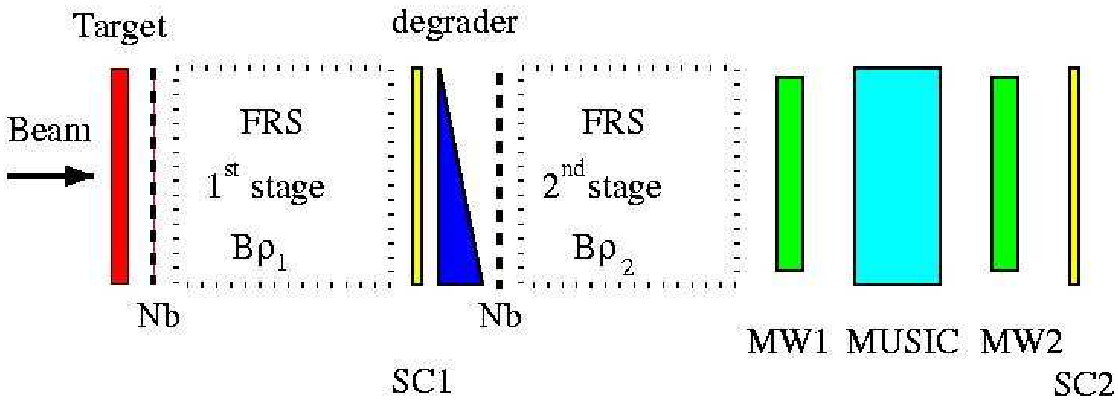

Fig.1: *Schematic drawing of the projectile fragment separator with the standard detector set-up for in-flight identification of ions prior to the secondary target.*

Experiments with relativistic beams

After passing the identification set-up, the radioactive ions at relativistic energies are focused on a secondary target, which will be positioned approximately 4m after the last FRS-quadrupole. For experiments with beam energies around 100MeV/u the Ge-detectors have to be positioned at forward and backward angles in order to minimize the Doppler broadening effect. The best possible Euroball detector configuration for experiments with fast beams is displayed in figure 2. For the required gamma-ray energy resolution of about 1% the15 Cluster Ge-detectors without BGO shields have to be positioned in three rings which yield a total efficiency of 1.67%. The calculated efficiency for a 1.3MeV gamma-ray energy (rest frame) includes relativistic effects when the gamma-rays are emitted in flight (v/c=0.43). The present configuration is detailed below:

Ring #1	5 Clusters	ϑ=15°	r=68.0cm
Ring #2	5 Clusters	ϑ=26.5°	r=111.9cm
Ring #3	5 Clusters	ϑ=34°	r=136.9cm

Due to the Lorentz boost the main efficiency contribution comes from the first ring. This ring is positioned to achieve 1% resolution within the constraints of the beam pipe diameter of 16cm. One should note that the 5 Clusters in the 2nd and 3rd rings could be moved closer to the target position, for an increased efficiency but a lower overall resolution. If both rings are placed at a minimum distance of ~70cm then the configuration will reach a total efficiency of 2.9% while the average weighted energy resolution is only slightly increased to 1.24%.

At backward angles a wall of 26 Clover Ge-detectors could be installed. However, the Clover array contributes only 35% to the total efficiency. Therefore it was decided not to use these detectors in the fast beam experiments and to reserve this space for measurements with a BaF array.

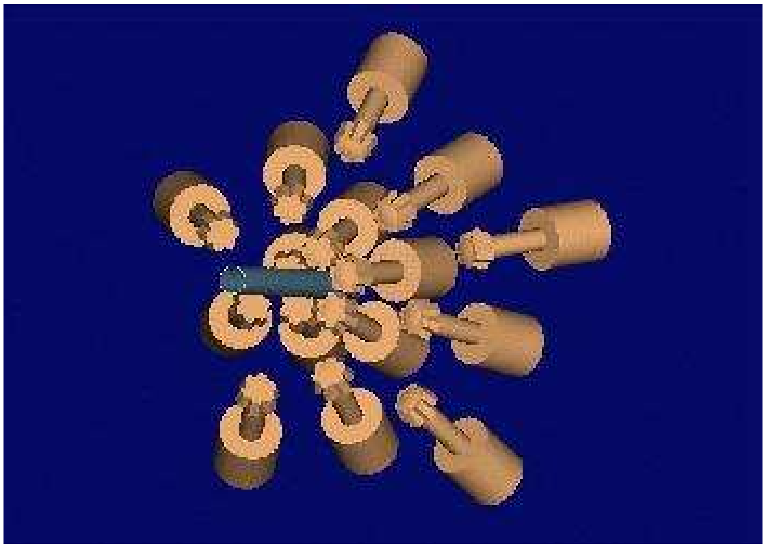

Fig. 2: *Configuration of 15 Cluster Ge-detectors without BGO shields for experiments with relativistic beams.*

For the fragment identification after the target measurement with a position sensitive Si-array and a thick scintillator is planned, in order to provide horizontal and vertical position, energy-loss and total energy information. While the atomic number Z can be determined uniquely, the total energy measurement (FWHM~1%) will yield only a moderate mass resolution sufficient for the proposed experiments with medium heavy nuclei. For the heavier fragments projectile decay tagging is suggested which allows fragment identification due to its isomeric decay. The two-dimensional position information of the Si-array will also yield the scattering angle of the Coulomb excitation process. An alternative site for the proposed experiments is the ALADIN-LAND set-up which allows a magnetic analysis of the fragments and neutron detection (ε_n~60% for $E_n \leq$ 100MeV) after the secondary target. The necessary mass resolution may, however, not be reached with heavy ions because of the charge changing interactions in the target at beam energies of 100~MeV/u. If the charge state would be preserved in the target, a mass resolution of 1/200 could be expected. Finally, the RIB intensities available in Cave B or C will be lower by about one order of magnitude relative to the site just behind the FRS because of the missing high transmission beam line.

Experiments with slowed down beams

After passing the identification set-up (100~MeV/u), the RIB can be slowed down in an adjustable aluminium degrader in order to perform experiments at the Coulomb barrier. The proposed experimental set-up is shown schematically in figure 3. The decelerated ions will be deflected magnetically by 10-30 degrees. This ensures that light ions (p,n,etc) produced by nuclear interactions during the slowing down process and the prompt photon flash, as described below, can be shielded from the Ge detector array. Additional quadrupole lenses Q2 are needed to refocus the low energy beam on the secondary target. Three position sensitive parallel plate avalanche counters PPAC serve for both beam tracking and time-of-flight measurements. The latter result allows the selection of an energy range for fusion and Coulomb excitation experiments. For both types of experiments the Ge-detectors can be arranged in a more symmetric configuration in order to obtain a higher total efficiency at a gamma-ray energy resolution of 1%.

The experimental set-up can be combined with a plunger for lifetime measurements, a Si implantation detector which allows fragment identification by recoil decay tagging and a Si ball for light charged particles.

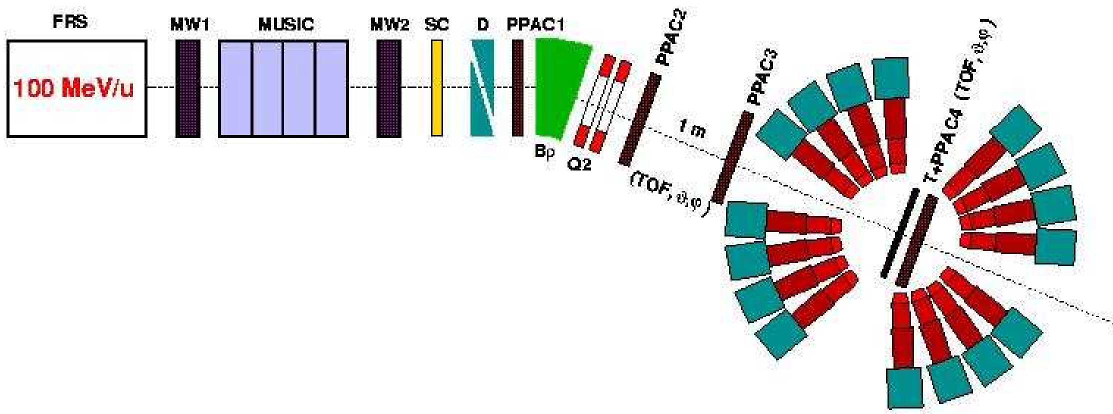

Fig. 3: *Schematic drawing of the experimental set-up for slowed down beams.*

Decay experiments

For decay experiments the identified radioactive ion beams will be slowed down at the final focus of the FRS using an adjustable aluminium degrader and subsequently implanted in a position sensitive Si catcher array. Two additional plastic scintillators will be mounted, either side of the catcher and used in order to verify that all selected ions are stopped in the catcher. The energy-loss signal from the first scintillator can also be used for off-line suppression of events resulting from nuclear interactions of ions during the slowing down process. Employing detectors developed within the GREAT (**G**amma-**R**ecoil-**E**lectron-**A**lpha-**T**agging) project will enable measurement of α- and β-particles from the decay of the implanted ions as well as X-rays and conversion electrons. The set-up will be surrounded by an array of Cluster and Clover Ge-detectors, in which delayed gamma-rays emitted by the implanted ions will be detected. This array will be a compact, box-like configuration of Ge-detectors.

The stopping process of heavy ions in the degrader and catcher is usually accompanied by a prompt burst of radiation, mainly due to X-rays and bremsstrahlung (M_γ ~10). By blocking Ge-detectors hit by prompt quanta the effective efficiency for delayed quanta will be reduced unless the number of detectors is large compared to the prompt multiplicity. Therefore RISING with its 100-200 Euroball detectors is adequate to preserve the efficiency. The expected full energy efficiency of the gamma-array will be >10% while the gamma-ray energy resolution is determined by the intrinsic resolution (2-3 keV) of the individual Ge-detectors.

The flight time of the ions through the separator is about 300 to 400 ns, which sets a lower limit of about 100~ns for the lifetimes which can be studied. For some special cases, this lifetime limit may be considerably shorter (~10 ns) when the electron conversion branch is blocked in a highly stripped ion. The upper limit of the isomer spectroscopy is determined by the RIB intensity. For very exotic nuclei with rates well below 1 kHz lifetimes up to the ms range can be measured.

For the g-factor measurements of isomeric states a dedicated magnet system up to 1 Tesla will be developed. The Euroball detectors will be placed around the magnet.

6. Project Realization

As indicated in the previous section experimental set-ups radically different from previous Euroball set-ups have to be developed and built to be able to perform the anticipated physics program.

Development Tasks

- Geometrical arrangements of the Ge-detectors
- Novel high rate, in-vacuum FRS tracking detectors
- Slowing down method with subsequent gamma-spectroscopy
- Adequate electronics and data acquisition system
- Ancillary detectors

Cost and Effort

Novel FRS tracking detectors, a variety of ancillary detectors, new mechanical structures, a new cooling system and at least partially new electronics is being developed and built. Otherwise, most of the previous investment in Euroball will be re-used in the RISING project. Therefore it appears that in particular the cost but also the effort of the project is only a fraction of the previous total investment in the Euroball detectors and their experimental infrastructure. Running costs will be similar to Euroball.

Time plan

The fast beam set-up time can be realized by the end of 2002, enabling the Euroball detectors to be employed for experiments at GSI in early 2003. The stopped beam campaign relies on detectors currently being developed within the GREAT project. Such detectors become available later in 2003 suggesting stopped beam experiments to come next. Finally to optimise the slowing down of RIB's requires systematic studies and time consuming preparations. Therefore this campaign should come last. Taking into account the project effort on one hand and the restrictions imposed on other experimental programs at GSI on the other hand a sensible period for the Euroball detectors to stay is 2-3 years. This implies experimental campaigns to last for at least 9 months each.

Appendix A

List of institutions collaborating in RISING

HMI Berlin, Germany
Univ. Bonn, Germany
GANIL, Caen, France
Univ. Camerino, Italy
IFJ Cracow, Poland
CLRC Daresbury, UK
GSI Darmstadt, Germany
Univ. Demokritos, Grecce
Univ. Firenze, Italy
INFN Genova, Italy
MPI Heidelberg, Germany
FZ Jülich, Germany
Univ. Köln, Germany
INFN Legnaro, Italy
Univ. Leuven, Belgium
Univ. Liverpool, UK
Univ. Lund, Sweden
Univ. Manchester, UK
Univ. Milano, Italy
LMU. München, Germany
TU. München, Germany
INFN/Univ. Napoli, Italy
CSNSM Orsay, France
IPN Orsay, France
INFN/Univ. Padova, Italy
Univ. Paisley, UK
FZ Rossendorf, Germany
CEA Saclay, France
Univ. Stockholm, Sweden
Univ. Surrey, UK
IPJ Swierk, Poland
Univ. Warsaw, Poland
Univ. Uppsala, Sweden
Univ. York, UK

Appendix B

Variety of proposed experiments

The presented papers reflect ideas discussed during the physics workshops and generously written down by participants. This selection is not meant to be exclusive.

1. Fast Beams

1a) **New (sub) shell closures – Relativistic Coulex of neutron-deficient and neutron-rich Ca isotopes**

1b) **Neutron-rich isotopes in the Ni region studied with fast beams using RISING**

1c) **Physics of N~Z nuclei with fast beams at RISING**

1d) **Study of proton drip line nuclei above Z = 50**

1e) **Shape evolution in light n-rich nuclei**

1f) **Magnetic moments of short-lived states in radioactive nuclei following Coulomb excitation at relativistic energies**

1g) **Prompt gamma spectroscopy and isomer tagging; Deformation of isomeric states in the A=180-200 region**

1h) **Gamma-decay of the GDR in Coulomb excited exotic nuclei**

2. Stopped Beams

2a) **Structure Around ^{100}Sn**

2b) **g-Factor Measurements**

2c) **Proton Drip line physics around A~130**

2d) **Fission fragment studies: Opportunities with RISING** *M.*

2e) **The Neutron-rich Hf-Pt region**

2f) **Isomer and Particle Decay Probes of Shape Coexistence Around Z=82**

3. Slow Beams

3a) **Measurement of B(E2)-values by Coulomb excitation of secondary beams slowed down to the Coulomb barrier**

3b) **Measurement of B(E3) moments in octupole nuclei**

3c) **Coulex RDDS experiments with radioactive beams**

3d) **Collectivity studies in fully aligned Isomeric sates**

3e) **Spectroscopic factors for single nucleon transfer on magic nuclei with slow beams at RISING**

3f) **Single particle transfer and pairing in dripline nuclei**

3g) **Neutron breakup reactions**

3h) **Reaction Mechanism Experiments using the GSI slow RIBs**