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# Status of the RISING project at GSI

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**Abstract.** The FRS-RISING set-up at GSI uses secondary radioactive beams at relativistic energies for nuclear structure studies. At GSI the fragmentation or fission of stable primary beams up to $^{238}$U provide secondary beams with sufficient intensity to perform $\gamma$-ray spectroscopy. The RISING set-up is described and results of the first RISING campaign are presented. New experimental methods at relativistic energies are being investigated. Future experiments focus on state-of-the art nuclear structure physics covering exotic nuclei all over the nuclear chart.

**PACS.** 25.70.De Coulomb excitation – 25.70.Mn Projectile and target fragmentation – 29.30.-h Spectrometers and spectroscopic techniques – 29.30.Kv X- and $\gamma$-ray spectroscopy

## 1 Introduction

The RISING (Rare ISotope INvestigations at GSI) set-up [1] consists of the fragment separator FRS [2] and a highly efficient $\gamma$-ray spectrometer. EUROBALL Ge-Cluster detectors [3] together with $BaF_2$ detectors from the HECTOR array [4] form the $\gamma$-ray array which is placed at the final focus of the FRS. The SIS/FRS facility [2] provides secondary beams of unstable rare isotopes produced via fragmentation reactions or fission of relativistic heavy ions. These unique radioactive beams have sufficient intensity to perform $\gamma$-ray spectroscopy measurements. In the first campaign fast beams in the range of 100 to 400 $A \cdot$ MeV were used for relativistic Coulomb excitation and secondary fragmentation experiments.

Coulomb excitation at intermediate energies is a powerful spectroscopic method to study low-spin collective states of exotic nuclei [5]. It takes advantage of the large beam velocities and allows the use of thick secondary targets. Unwanted nuclear contributions to the excitation process are excluded by selecting events with forward scattering angles corresponding to sufficiently large impact parameters. Contrary to Coulomb excitation, fragmentation and nucleon removal reactions at the secondary target are a universal tool to produce exotic nuclei in rather high spin states [1]. Besides being an excellent tool to investigate radioactive fragments up to higher spin states, fragmentation reactions provide a selective trigger, particularly suppressing the strong background of purely atomic interaction events. For the first fast beam campaign the RISING set-up was optimized to the study of the following subjects of exotic nuclei: the shell structure of nuclei around doubly magic $^{56}$Ni and $^{100}$Sn, the evolution of shell structure towards extreme isospin, the investigation of shapes and shape coexistence in particular around the $N = Z$ line and the mirror symmetry, as well as collective modes and the $E1$ strength distribution in neutron-rich nuclei ($N \gg Z$).

## 2 Experiments

### 2.1 Experimental details

The SIS facility at GSI provides primary beams of all stable nuclei up to $^{238}$U. For various nuclei a projectile energy up to 1 $A \cdot$ GeV and intensities up to $10^9$/s are available. Radioactive beams are produced by projectile fragmentation or fission of $^{238}$U. From the exotic fragments

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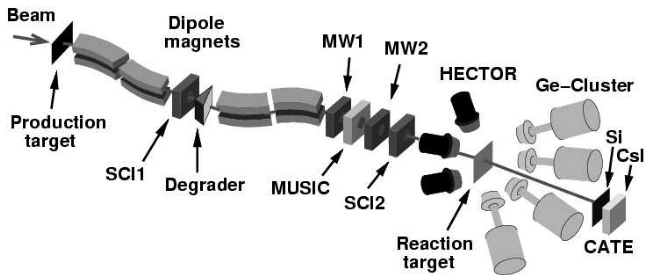


**Fig. 1.** Schematic sketch of the FRS-RISING set-up. Two multiwire detectors (MW1 and MW2), an ionization chamber (MUSIC), and two scintillator detectors (SCI1 and SCI2) are the beam diagnostic elements for the FRS. $\gamma$-rays produced in the reaction target at the final focus of the FRS are measured with $BaF_2$-HECTOR and Ge-Cluster detectors. The CATE array identifies the outgoing reaction products by mass and charge.

produced, the nuclei of interest are selected by the FRS using the combined $B\rho$-$\Delta E$ technique [2]. The RISING set-up at the FRS is shown schematically in fig. 1. For the FRS beam diagnostics, scintillator detectors (SCI), an ionization chamber (MUSIC), and multiwire detectors (MW) are employed to identify the produced ions and select the nucleus of interest. The position-sensitive SCI detectors determine the time-of-flight (TOF) and together with the MWs the position of the beam in the FRS. From the TOF and the flight path length, the velocity of the ion is determined. The MUSIC detector measures the energy loss of the ions and gives the atomic number $Z$. Together with the ion velocity a particle identification in $Z$ and $A/Q$ is achieved. At the final focal plane of the FRS, a reaction target is placed. In all Coulomb excitation experiments this was a gold target, while for the secondary fragmentation experiment a $^{9}$Be target was used. To identify type and track of the particles hitting the secondary target, the two MWs placed upstream were applied. The outgoing particles were identified in charge and mass by the calorimeter telescope CATE [6,7,8], a Si-CsI array. The position-sensitive Si detectors of CATE allow tracking of the outgoing particles required for the scattering angle selection in the Coulomb excitation experiments and for the Doppler correction procedure. In order to perform $\gamma$-ray spectroscopy a highly efficient $\gamma$-ray array was placed in the view of the reaction target. It consists of EUROBALL Cluster Ge detectors [3] and $BaF_2$ detectors from the HECTOR array [4]. The Cluster detectors benefit from being placed under forward angles between 15 and 36 degrees, since the Lorentz boost increases the $\gamma$-ray efficiency from 1.3% measured with a $^{60}$Co source at rest to 2.8% (at 100 $A \cdot$ MeV) for the in-beam studies at relativistic energies. A distance of 70 cm between the Ge detectors and the target is necessary for an energy resolution between 1–3% after Doppler correction.

### 2.2 Present results

In a commissioning experiment a primary $^{84}$Kr beam was used. The aim was to investigate the feasibility of Coulomb excitation measurements under the present conditions. The $2^+ \to 0^+$ transition in $^{84}$Kr was employed to study the impact parameter dependence at relativistic energies. From the $\gamma$-array design about 1% energy resolution is expected for a $\gamma$-ray emitted from a moving nucleus with $\beta \sim 0.4$ [1]. The commissioning with a primary $^{84}$Kr beam confirms the expected energy resolution of $\sim 1.5\%$ for the Doppler-corrected $2^+ \to 0^+$ transition at 884 keV ($\beta \sim 0.4$).

Relativistic Coulomb excitation measurements with secondary beams were performed to measure for the first time $B(E2)$ values of first excited $2^+$ states. Excitation of $^{54,56,58}$Cr was chosen in order to investigate the shell structure of nuclei with extreme isospin. The secondary beam was produced by fragmentation of a primary $^{84}$Kr beam. In another experiment fragmentation of a primary $^{124}$Xe beam produced secondary $^{108,112}$Sn beams. The measurement of the electromagnetic $2^+ \to 0^+$ transition probability in the neutron-deficient nucleus $^{108}$Sn gives insight in the nuclear structure towards $^{100}$Sn. It is a sensitive test of $E2$ correlations related to core polarization. The known $B(E2)$ value in $^{112}$Sn is used for normalization.

Secondary fragmentation was used to study the mirror pair $^{53}$Mn/$^{53}$Ni. The identification of the so far unknown first excited states in $^{53}$Ni would provide information on isospin symmetry and Coulomb effects at a large proton excess as well as a rigorous test of the shell model. Secondary beams of $^{55}$Ni and $^{55}$Co were produced by fragmentation of a primary $^{58}$Ni beam. The fragmentation of the secondary beams produced many exotic nuclei, among them the nuclei of interest $^{53}$Mn and $^{53}$Ni.

Compared to primary beams, secondary beams have a broader momentum distribution. In order to achieve a good energy resolution an accurate vertex reconstruction of incoming and outgoing particles is required. The analysis of the relativistic Coulomb excitation of $^{54}$Cr provides an example [9]. The energy resolution of the 834 keV transition in $^{54}$Cr could be improved from $\sim 4\%$ to $\sim 2\%$ without and with vertex reconstruction for the Doppler correction procedure, respectively.

Figure 2 shows the $\gamma$-ray spectra of $^{54,56,58}$Cr. The intensities of the clearly visible $2^+ \to 0^+$ transitions are a measure of the $B(E2)$ strength which reveals information on the evolution of a possible $N = 32$ sub-shell closure. A detailed publication on the $B(E2)$ values can be found in references [10,11]. The relativistic Coulomb excitation study of $^{108}$Sn revealed for the first time the $B(E2)$ value for the $2^+ \to 0^+$ transition [12].

Concerning the two-step fragmentation of the $^{55}$Ni and $^{55}$Co secondary beams, the ongoing analysis reveals so far the mirror pair $^{54}$Fe and $^{54}$Ni, this is presented in fig. 3. The spectra acquired from $\approx 50\%$ of the data show good statistics and complement previous experiments on $^{54}$Ni obtained in a recent EUROBALL experiment [13] and intermediate-energy Coulomb excitation studies at NSCL [14]. The resolution of the $\gamma$-ray lines in fig. 3 is inferior to that of the $\gamma$-ray lines shown in fig. 2 due to the different reaction process. The goal to obtain $^{53}$Mn/$^{53}$Ni with a factor 50–100 lower cross-section could be reachable

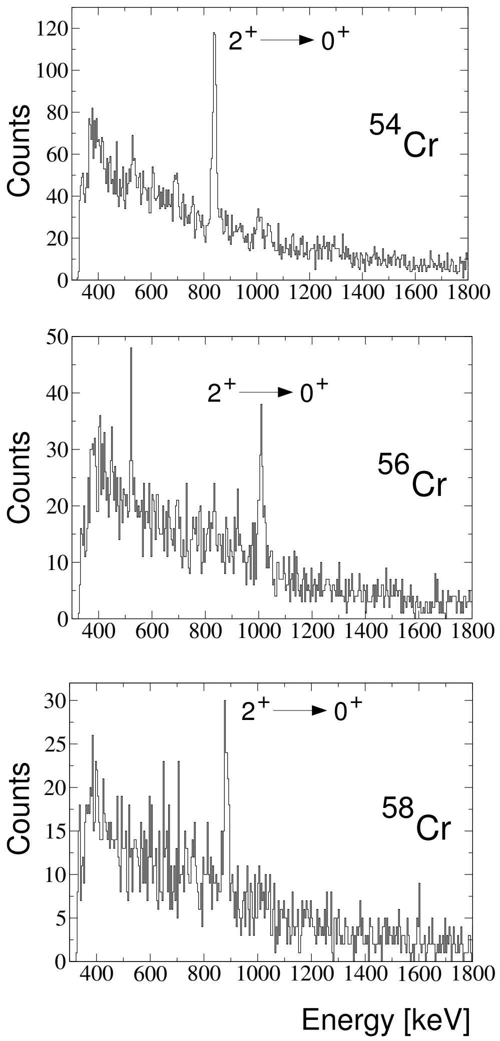


**Fig. 2.** Relativistic Coulomb excitation: $\gamma$-ray spectra of $^{54,56,58}$Cr [10,11].

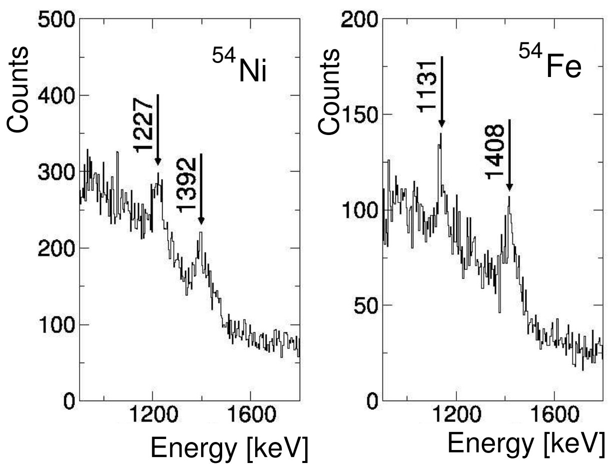


**Fig. 3.** Exotic nuclei produced by secondary fragmentation reactions: $\gamma$-ray spectra were obtained for $^{54}$Ni (left) and $^{54}$Fe (right) [15].

with an improved analysis using the full statistics, a refined tracking Doppler correction, and in particular an improved mass determination [15].

The mass resolution in the secondary fragmentation reactions is limited by the accuracy of the momentum distribution determination of the projectile fragments. According to the statistical model derived by Goldhaber [16] the mass resolution of fragments at 100 $A \cdot$ MeV amounts to 2–3% (FWHM) without a momentum or time-of-flight measurement. With the actual CATE set-up we could achieve a mass resolution of the 2–3% for fragmentation and 1–2% for Coulomb excitation reaction channels [8].

From recent experiments we have the following online results. The structure of neutron-rich Mg nuclei is being investigated by lifetime measurements. In the chain of the Mg isotopes strong prolate deformations are expected. $B(E2)$ values of excited states deduced from lifetimes will be a measure of the deformation. The experiment takes advantage of the high abundance of nuclei produced via a two-step fragmentation reaction. According to the expected lifetime a stack of three targets has to be arranged at well defined distances. This allows the extraction of the lifetimes of states in the picosecond range by analysing the specific $\gamma$-ray line shapes.

The $A \approx 130$ region shows strong evidence for the existence of stable triaxial shapes [17]. This is indicated in this transitional region by the observation of chiral doublet structures in the odd-odd $N = 75$ isotones [18]. $N = 74$ even-even nuclei $^{132}$Ba, $^{134}$Ce and $^{136}$Nd are good candidates since they are cores of the $N = 75$ odd-odd nuclei $^{132}$La, $^{134}$Pr and $^{136}$Pm where chiral doublet bands were observed. Relativistic Coulomb excitation of the even-even nuclei are being performed within the RISING campaign. The measurement of the $B(E2)$ values of the transitions depopulating the $2_1^+$ and $2_2^+$ states will provide a sensitive test for the results of the Monte Carlo shell model. The calculations predict comparable strengths for the $B(E2)$ values of the $4_1^+ \rightarrow 2_1^+$ and the $2_2^+ \rightarrow 2_1^+$ transitions as a fingerprint of the underlying triaxiality [19].

A technical upgrade is a detector behind the reaction target, an additional CATE $\Delta E$ Si detector. Compared to the vertex reconstruction achieved with the MW detectors 3 m upstream of the reaction target, the accuracy of the position determination at the target was improved from 1 cm to 3 mm (FWHM). Measuring twice the $\Delta E$, at the target and at CATE, enhanced the measured $Z$ resolution by a factor 1.4.

## 3 Perspectives

The differential Doppler shift method applied for the neutron-rich Mg isotopes can also be employed in the light Pb isotopes. The proposed investigation on $^{185,186,187}$Pb would probe the scenario of the predicted triple shape coexistence by the experimental determination of the deformation parameters. The lifetime information on the first excited states could again be extracted from the $\gamma$-ray line shapes produced in a secondary fragmentation reaction.

The investigation of collective modes in nuclei far from the stability line is still in its infancy. In the neutron-rich nuclei the p-n asymmetry could influence the shell structure. Predictions by theory point to changes in the giant dipole resonance (GDR) strength distribution in exotic neutron-rich nuclei like $^{68-78}$Ni. The GDR is supposed to fragment the strength towards lower excitation energy, the so called Pygmy resonances. The RISING set-up provides besides the Ge-Cluster also $BaF_2$ detectors. The latter permit the measurement of $\gamma$-rays at relatively high energies making it possible to cover the entire dipole response function. The measurement of the $\gamma$-ray decay stemming from GDR is a proposed RISING experiment on $^{68}$Ni.

Further it is planned to investigate the structure of neutron-rich nuclei with respect to mixed symmetry [20]. IBM-2 calculations predict mixed-symmetry states in the $N = 52$ isotones, *i.e.* non-symmetric states with respect to the p-n degree of freedom. To study the evolution of this structure at $N = 52$ below $Z = 40$ suggests an investigation of the neutron-rich nuclei $^{88}$Kr and $^{90}$Sr. Relativistic Coulomb excitation experiments could reveal the $B(E2)$ values for the predicted low-lying first and second excited $2^+$ states. The $2^+_2$ value would be a sensitive test for detailed shell model and IBM-2 calculations and would contribute to understand the evolution of mixed-symmetry configurations [21].

A possible weakening of the spin-orbit splitting resulting in a restoration of the harmonic-oscillator shell closures is predicted by theory for very neutron-rich nuclei [22]. In this scenario the harmonic-oscillator magic numbers would supersede the magic numbers based on the Woods-Saxon potential well known for nuclei close to stability. For the neutron-rich Ni and Sn isotopes the information on the most significant matrix elements, magnetic moments and spectroscopic factors are up to now not available. RISING will contribute revealing these sensitive pieces of nuclear structure information.

An investigation of the nuclear structure in the vicinity of $^{132}$Sn is a good testing ground for the evolution of the spin-orbit splitting [23]. For neutron-rich nuclei far from stability this splitting is predicted to decrease or vanish [22]. The RISING set-up offers the opportunity to determine the information on the spin-orbit splitting by the measurement of the spectroscopic factors. It is proposed to measure spectroscopic factors in $^{131}$Sn by a neutron removal reaction of a radioactive $^{132}$Sn beam produced by fission of $^{238}$U.

The structure of the unstable neutron-rich isotopes $^{132,134,136}$Te is strongly influenced by the $N = 82$ shell closure and two protons outside the magic $Z = 50$ shell [24]. Measurements of $g$-factors performed within the RISING project would yield the information on the dominant role of protons or neutrons being involved in the configurations of the first excited states. A comparison with predictions by theory would give the information on the specific components induced by neutron and proton orbitals. The proposed measurement of perturbed $\gamma$-ray angular correlations for lifetimes in the picosecond range is at present only feasible by the technique of transient magnetic fields (TF). The future $g$-factor experiment will employ the relativistic Coulomb excitation of secondary $^{132,134,136}$Te beams in combination with the TF technique.

Spectacular is the observation of an anomalous Coulomb energy difference behaviour in the $N = Z$ nucleus $^{70}$Br [25]. Coulomb distortion of the nucleon orbitals is indicated (Thomas-Ehrman shift). This effect should increase as the drip line is approached. The RISING proposal on the supposed proton emitting nucleus $^{69}$Br would allow the investigation of the heaviest mirror pair $^{69}$Br/$^{69}$Se at the proton drip line. Moreover $^{69}$Br plays an important role in the rapid-proton capture (rp) process. The odd-$Z$ isotope $^{69}$Br is considered as being a possible termination point in the rp-process when the proton capture lifetime of the $^{68}$Se target is longer than competing decays and the proton flux duration. Previous experiments [26,27,28] could not attribute clear evidence for the stability of $^{69}$Br due to difficulties of the flight path limit. In the proposed RISING experiment an investigation of the prompt production in a secondary fragmentation reaction would overcome this limitation. At the same time the measurement of the prompt $\gamma$-ray decay would give insight into mirror pair properties at the proton drip line.

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