

STATUS OF THE RISING PROJECT AT RELATIVISTIC ENERGIES*

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The RISING project was designed to perform high-resolution γ -ray spectroscopy with radioactive beams at GSI. Unstable beams were produced by fragmentation of relativistic heavy ion projectiles provided by the SIS synchrotron. The fragment separator FRS was used to select and to focus the exotic fragments at about 100 A MeV energy on a secondary target. Various charged particle detectors enabled an event-by-event tracking of the incoming radioactive projectiles and the reaction products, thus allowing for a selection of the nuclei of interest and their velocity vector reconstruction. The γ -ray detection system consisting of the EUROBALL Cluster Ge detectors and the large volume HECTOR BaF₂ detectors measured prompt γ -radiation from nuclei excited in the secondary target. Despite the huge Doppler shift due to the high recoil velocity ($\beta \approx 40\%$), RISING achieved a γ -energy resolution below 2%. The paper reviews the present status of the RISING project.

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1. Introduction, γ -spectroscopy studies with radioactive beams

Nuclei with an extreme N/Z ratio are expected to exhibit features not observed near the stability line. By studying the structure of unstable nuclei one can significantly extend the knowledge of nucleon–nucleon interactions, nuclear symmetries, and collective excitation modes. Therefore, the exploration of exotic regions of the nuclear chart becomes a key issue of current and future research projects in the nuclear γ -spectroscopy domain.

Nowadays, rare nuclei so far inaccessible by conventional fusion-evaporation or transfer reactions, can be created in-flight by peripheral nuclear collisions. Primary beams at intermediate energies ranging from a few ten to several hundred A MeV are of use. The relativistic projectile impinging on a primary-production target undergoes fragmentation. In this way, exotic fragments with a large proton or neutron excess are produced. More neutron rich nuclei originate from fission of heavy projectiles such as ^{238}U , induced by the Coulomb scattering on a heavy target.

The in-flight technique relies on a forward focusing of the reaction products and a high production yield due to the use of thick targets. Large acceptance electromagnetic separators selecting the exotic fragments of interest provide isotopically pure radioactive ion beams (RIB) [1].

The in-beam γ -decay of the excited rare projectiles can be studied [2]. On the other hand, the investigation of secondary nuclear reactions induced by the RIB is feasible [3].

Pioneering γ -spectroscopy experiments with RIB produced by the in-flight method were performed at GANIL [4] and GSI [5] in Europe, NSCL–MSU [6] in the USA, and RIKEN in Japan [7]. However, important limitations occurred due to the accelerator, the fragment separator, and the detector techniques applied so far.

GSI offers a wealthy choice of high-intensity heavy-ion beams, including uranium, at a wide range of energies. They can be used to produce secondary projectiles through either fragmentation or fission, suitable for in-beam investigations. This, together with the availability of the most powerful γ -ray detection system, the EUROBALL Ge array [9], could be considered as a breakthrough in the discipline. A large international collaboration involving over 40 institutions from 10 countries launched the RISING (Rare ISotope INvestigation at GSI) research program, aiming at high-resolution γ -ray spectroscopy with radioactive beams provided by the GSI facilities. Measurements with fast RIBs at 100 A MeV energy, exploring γ -decays of rare nuclei excited via the Coulomb scattering or secondary fragmentation reactions are presently being carried out. In future experiments, beams slowed down to Coulomb barrier energies for investigations of states excited in nuclear reactions and stopped beams for decay studies will be used.

The three aforementioned campaigns require not only an efficient γ -ray detection system but also a dedicated set of ancillary detectors selecting the reaction channel of interest and tracking the decay products. In the forthcoming paragraphs, a general description of the experimental techniques used at *RISING* with fast beams is presented. This includes the secondary beam separation, tracking of the reaction products and the γ -ray detection. The in-beam performance of the system is discussed. The technical details on the *RISING* setup for fast beams can be found in Ref. [8].

2. Radioactive beams at GSI and the *RISING* heavy ion tracking detector system

The SIS synchrotron of GSI provides all the primary beams up to ^{238}U [11]. The heavy ions can be accelerated up to 1 A GeV and reach intensities of 10^9 particles per second. Depending on the requested secondary ion, the relativistic projectiles interacting with the production target nuclei may be fragmented or undergo fission.

The fully stripped fragments of interest produced in the reaction are separated in the fragment separator (FRS) by the $B\rho - \Delta E - B\rho$ technique [10]. The FRS consists of two mirror sets of dipole and quadrupole magnets. Each part selects heavy ions according to the A/Q ratio. A degrader placed in the intermediate focal plane of the separator introduces a fragment velocity dispersion due to the specific energy loss of different elements. Therefore, the fragments with the particular A and Q are focused onto a secondary target placed in the final focal plane of the FRS.

The exotic beams obtained in a projectile fragmentation reaction nearly retain the velocity vector of the primary ions. Thus, the typical transmission through the FRS is several ten per cent. In contrast, in fission reactions, the energy transferred to the fragments induces a spread of their velocity and direction, causing a reduction in the transmission to a few per cent maximum.

Due to low production cross sections, the intensities of radioactive beams may reach only 10^4 particles per second. Moreover, a momentum spread of the fragments makes the precise determination of the projectile trajectory and the energy difficult. Therefore, the optimization of the FRS settings and the online control is essential in obtaining a good quality radioactive beam.

In Fig. 1 a schematic plot of the FRS setup incorporating various particle detectors used for the secondary beam monitoring is shown. The ionization chamber MUSIC gives the proton number Z of the selected projectiles, whereas the fast plastic scintillator detectors provide the corresponding time of flight, allowing for a velocity and A/Q determination. The two position sensitive avalanche multiwire counters are used to determine the trajectory before the secondary target and to monitor the beam spot size and position.

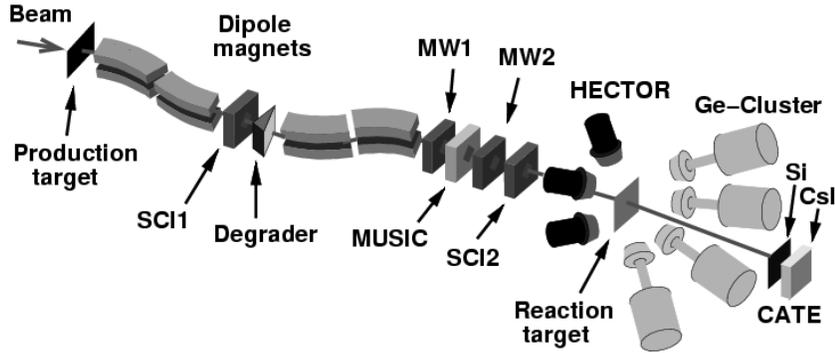


Fig. 1. Schematic layout of the RISING setup at the FRS fragment separator. The beam diagnostic elements consist of two multiwire detectors (MW1 and MW2), an ionization chamber (MUSIC) and two scintillation detectors (SCI1 and SCI2). The γ -rays are measured with the BaF₂-HECTOR and the Ge-Cluster detectors. The ions emerging from the reaction target are identified with the CATE array.

The full identification of the reaction products and their scattering angle after the secondary target plays a vital role in selecting the nucleus of interest from a dominating unwanted background. The high efficiency position sensitive $\Delta E - E$ telescope array CATE [12] was developed for RISING in order to determine A , Z and the position of detected heavy ions. CATE allows for measuring the full energy range of expected fragments with $Z > 7$. The detector angular acceptance from $\theta = 0^\circ$ to $\theta = 3^\circ$ is sufficient for detecting the Coulomb scattered nuclei up to the maximum grazing angle.

The interaction of heavy-ion beams at relativistic energies with matter causes electromagnetic radiation of the atomic origin such as bremsstrahlung, target-atom ionization, or radiative electron capture [13]. These atomic processes can be several orders of magnitude stronger than a nuclear level excitation. Depending on the projectile energy, the atomic background can extend up to several hundred keV. Therefore, to avoid the overlap with the energy range where γ -rays from excited nuclear levels are expected *i.e.*, $E_\gamma > 400$ keV, the secondary beam energy shall be limited to about $100A$ MeV.

3. RISING γ -ray detector arrays at the FRS focal plane

The $100A$ MeV energy fragments excited in the secondary reaction, emit γ -rays in flight with $\beta = 43\%$. In the laboratory coordinate system, due to the Lorentz velocity transformation, the electromagnetic radiation originating from the moving source is forward focused (Lorentz boosted). For this reason, the fifteen EUROBALL Cluster Ge detectors were placed at the forward angles between 15° and 36° , 70 cm from the secondary target. In order to increase the solid angle they were mounted without the antineutron shields. For the moving radiation source, such a geometry guarantees

a gain in efficiency by a factor of about 2.2 with respect to the isotropic photon emission at rest. Thus, taking into account the efficiency of 1.3% measured with the ^{60}Co source, the estimated overall value is about 2.8% at 1.3 MeV energy.

The very large recoil velocity induces the Doppler shift of $E/E_0 \approx 1.5$ and a significant broadening of γ -lines observed at the forward angles. Nevertheless, the use of the high-granularity encapsulated Cluster Ge detectors allows to maintain a good energy resolution of $\Delta E/E < 2\%$. Furthermore, the Cluster detectors enable the energy add-back that considerably increases the efficiency at high γ -energies [14]. For example, the measurement performed with a Pu- α -Be source giving gammas of 6.129 MeV energy, revealed a gain in the number of counts in the peak by a factor of two when using the add-back mode.

The *RISING* γ -detection system benefits from eight large volume BaF_2 counters from the HECTOR array [15]. The BaF_2 detectors are particularly suitable for measuring high-energy γ -rays, as originating from the GDR decay. Although HECTOR is installed at the backward angle of 142° , in the area not occupied by the Clusters, its high efficiency compensates the deficit due to the forward Lorentz boost of the γ -radiation emitted in flight. Consequently, γ -rays of a few MeV energy can be registered in the HECTOR array with an efficiency comparable to those of Clusters.

A photo of the *RISING* detector arrangement at the reaction target area is shown in Fig. 2.

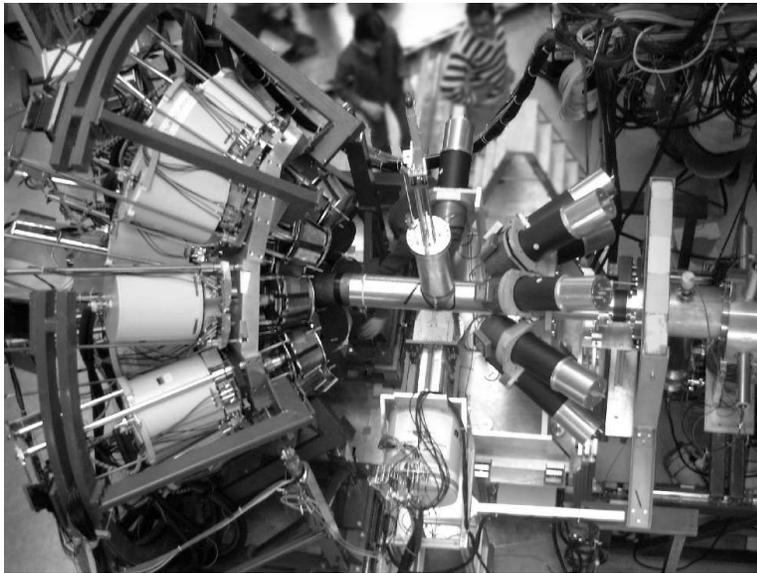


Fig. 2. The *RISING* γ -ray detectors placed around the reaction target. The BaF_2 HECTOR (right) and the Ge Cluster (left) arrays are shown.

4. In beam performance of the RISING system

The FRS/CATE heavy ion tracking detectors, the HECTOR array and the EUROBALL Cluster Ge detectors run as fully independent systems, with their original data acquisition being synchronized by time stamps.

Preparatory RISING measurements were done with the primary beams of ^{132}Xe , ^{84}Kr , and ^{40}Ar propagated through the FRS. The first in-beam tests permitted to adjust the subsystem settings and to elaborate the common particle- γ trigger selecting valid events in all the parts.

Further in-beam optimization of the RISING setup included suppression of the strong γ -radiation background arising from a beam scattering onto the beam-line components. Discrimination of gammas from the target and from a distant radiation source was possible due to a good time resolution of the HECTOR BaF_2 detectors. The most suitable arrangement of passive γ -ray detector shields was chosen.

Gamma rays from the Coulomb excited ^{84}Kr primary projectiles at 113A MeV hitting the 0.4 g/cm^2 Au target were detected in the Cluster detectors. A coincidence with the Kr ions selected by the CATE array was required. Using a fixed value of $\beta = 0.396$ for the Doppler correction, the measurement revealed an energy resolution of 1.5% for the 882 keV $2^+ \rightarrow 0^+$ transition in ^{84}Kr , as was expected from the setup design.

In contrast, when using a secondary beam, a fragment momentum spread occurs. However, it can be compensated by an event-by-event projectile tracking. The Coulomb excitation reaction of the secondary ^{54}Cr projectiles of 136A MeV energy on the Au target provides a good example, illustrating the tracking procedure.

The ^{54}Cr nuclei were obtained from the ^{86}Kr primary beam fragmentation and separated in the FRS. They were further selected before and after the reaction target by the MUSIC and the CATE detectors, respectively. The corresponding $Z - A/Q$ and $\Delta E - E$ scatter plots are presented in Fig. 3.

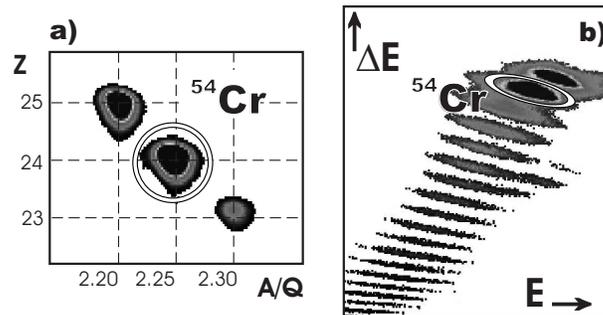


Fig. 3. The $Z - A/Q$ (a) and the $\Delta E - E$ (b) plots. The ^{54}Cr fragments were selected before and after the reaction target, respectively.

The projectile velocity used for event-by-event Doppler correction was determined from the time-of-flight measurement. The positions of a γ -ray detected by the Clusters and a scattered particle measured in CATE were recorded. However, due to the rather big size of the irradiated target area (see Fig. 4), in order to determine the actual γ -ray emission angle and the particle scattering angle, the trajectory of every incoming and outgoing Cr fragment had to be calculated.

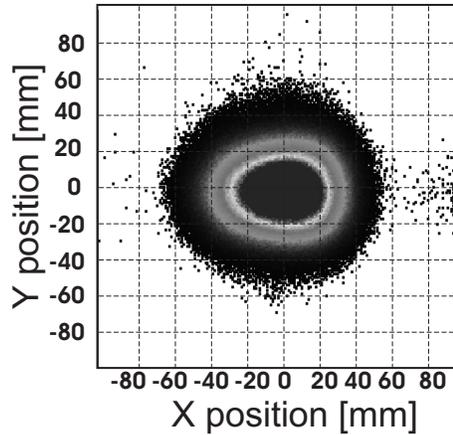


Fig. 4. Reconstruction of the secondary beam spot at the reaction target deduced from the multiwire position information. The irradiated area had a diameter of about 4 cm at FWHM.

The role of the projectile tracking in improving a γ -ray spectrum quality is illustrated in Fig. 5. For the measured 834 keV $2^+ \rightarrow 0^+$ transition in ^{54}Cr the overall energy resolution of $\text{FWHM} = 2\%$ was achieved when using the event-by-event particle tracking, whereas the average zero degree approximation resulted in resolution deterioration by a factor of nearly two.

The ^{54}Cr particle angular distribution measured in coincidence with the 834 keV gammas is shown in Fig. 6. The significance of the experimental points allows for comparison with the Coulomb excitation model calculations [16]. The plot clearly demonstrates an increase of the electromagnetic interaction cross section with increasing scattering angle up to the maximum grazing angle, where an absorption occurs.

A projectile scattering on the reaction target goes together with the Coulomb excitation of a target nucleus. The relative intensities of γ -transitions from the Coulomb excited levels in the target and the secondary beam nuclei can provide information on the decay probability of the studied projectile nuclei. In addition, a surveillance of the well known γ -rays emitted

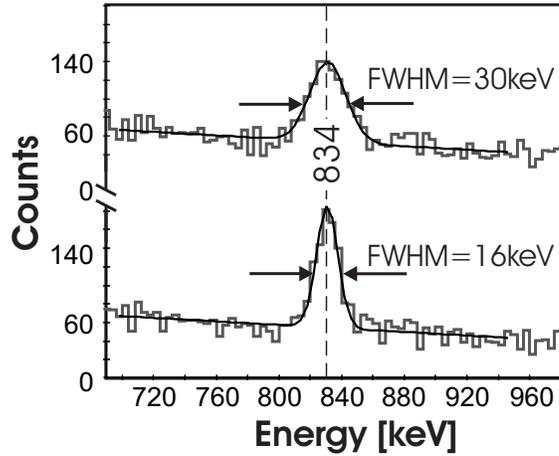


Fig. 5. The 834 keV γ -line from the ^{54}Cr Coulex after the Doppler correction using the event-by-event particle tracking (lower panel) and the zero degree scattering angle approximation (upper panel). In the lower spectrum the gain in energy resolution by a factor of about two is seen.

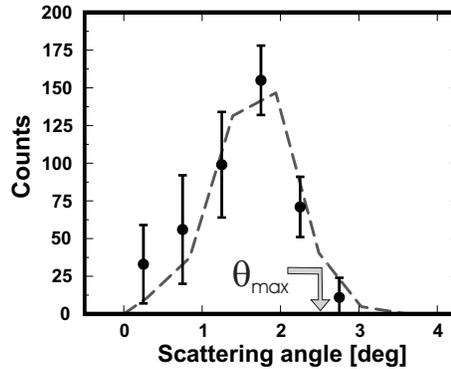


Fig. 6. The scattering angle of the ^{54}Cr fragments measured by the CATE array in coincidence with the 834 keV γ -rays. The experimental points follow the angular distribution predicted by the inelastic Coulomb scattering theory [16], normalized to the total number of counts, represented by the dashed line. The maximum Coulomb scattering angle θ_{max} is indicated.

at rest from the target can help in choosing the optimal measurement conditions as particle selection criteria and background suppression. In Fig. 7, the in-beam non Doppler corrected γ -spectra are shown. When measured in coincidence with the ^{54}Cr fragments, the weak 547 keV line from the ^{197}Au $7/2^+ \rightarrow 3/2^+$ decay emerges from the huge γ -ray background. The intensity ratio $I(^{197}\text{Au}; 547 \text{ keV})/I(^{54}\text{Cr}; 834 \text{ keV}) = 0.10 \pm 0.02$, determined from

the experiment, is in agreement with the relativistic Coulex code prediction [16]. In the calculation the reduced transition probabilities $B(E2)$ were taken from [17] and [18] for ^{197}Au and ^{54}Cr , respectively.

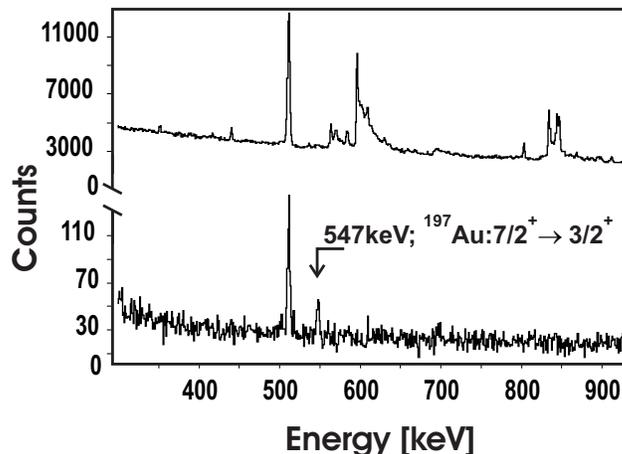


Fig. 7. In-beam non Doppler corrected γ -spectra measured without (upper panel) and with (lower panel) ^{54}Cr particle selection. The weak 547 keV γ -transition from the Coulomb excited ^{197}Au target nuclei appears due to a significant background suppression, when using the particle gate.

So far, in the course of the RISING fast beam campaign, mainly Coulomb excitation experiments were performed. They concerned the shell structure of neutron rich Cr isotopes [19] and Sn isotopes near the doubly magic ^{100}Sn nucleus [20]. An attempt at exciting the GDR resonance in the ^{68}Ni projectiles at 400 A MeV kinetic energy initiated the study of decays from highly-excited collective states in nuclei with large neutron excess [21]. Furthermore, a two-step fragmentation reaction of ^{58}Ni was used to investigate high-spin states in the $T_z = \pm 3/2$ mirror pair ^{53}Mn and ^{53}Ni [22].

5. Further development of the setup

In the future RISING experiments, the efficiency of the γ -detection system will be significantly increased by the inclusion of eight MINIBALL segmented germanium cluster detectors [23]. The high position sensitivity of the MINIBALL detectors allows for placing them relatively close to the secondary target at large angles, while at the same time a very good energy resolution of 0.3% can be maintained. The expected overall EUROBALL and MINIBALL efficiency at the 1.3 MeV energy for a γ -ray emitted in flight will be between 4 and 10 per cent, depending on the adjustable detector distance to the target.

6. Conclusion

RISING made use of unique radioactive beams at relativistic velocities available at the SIS/FRS facilities at GSI. The setup demonstrated the feasibility of high resolution γ -ray spectroscopy studies of nuclei excited either by Coulomb scattering or by fragmentation of relativistic radioactive beams. The first physics results concerning exotic atomic nuclei were obtained.

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