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Gamma spectroscopy with RIBs from RISING to AGATA

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Abstract. Nuclear spectroscopy using radioactive isotope beams requires dedicated set-ups. State-of-the-art Ge arrays recently started to provide valuable γ spectroscopic data. At the SIS/FRS facility at GSI exotic beams at relativistic energies were employed for Coulomb excitation and secondary fragmentation experiments with the fast beam RISING set-up. Shell evolution far off stability, pn-pairing, symmetries and nuclear shapes were studied in nuclei ranging from ^{36}Ca to ^{136}Nd. The observation of a I = 27 $\hbar$ state demonstrated that high spin states can be reached in massive fragmentation reactions. This and the large sensitivity of relativistic in-beam experiments opens a rich ground for advanced nuclear structure studies. Combining RISING with AGATA γ-tracking detectors and improved particle detection is planned for future experimental investigations.

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1 Introduction

Key subjects of contemporary and future nuclear structure research include:

- shell structure of known and predicted doubly magic nuclei and nuclei in their vicinity far off stability,
- isospin symmetry along the N = Z line and mixed symmetry states,
- deformed shapes and shape coexistence,
- collective modes of nuclear excitation and E1 strength distribution,
- nuclear moments.

Rare isotope beams (RIB) from both ISOL and fragmentation accelerator facilities together with high resolution γ-ray spectroscopy provide the means for experimental studies in this field. This contribution focuses on the current spectroscopy activities at GSI, i.e. the RISING [1] project at the SIS/FRS fragmentation facility, and discusses future perspectives with FAIR/NUSTAR [2] and AGATA [3].

2 The RISING experiment

The RISING project started in 2003 with a series of in-beam experiments employing RIBs at relativistic energies. In fall 2005 the set-up was modified to enable g-factor experiments with stopped beams. Since early 2006 decay experiments are being pursued.

The RISING γ spectroscopy set-up uses rare isotope beams from the SIS/FRS facility. Primary heavy ion beams provided by the heavy ion synchrotron SIS with a typical energy of 400–900 A$\cdot$ MeV impinge on a production target at the entrance of the fragment separator FRS. Fragments of interest are selected and identified in-flight on an event-by-event basis using their magnetic rigidity Bρ, their time of flight between the two scintillation detectors SCI1 and SCI2, see figure 1, and their energy loss in the multi sampling ionization chamber MUSIC. In order to optimize the secondary beam at the final focus, a wedge-shaped aluminium degrader is placed at the middle focal plane of the FRS. The multiwire detectors MW1 and MW2 serve to determine the position and direction of the beam particles in order to obtain the interaction point at the secondary target. Be or Au targets of several 100 mg/cm^2 thickness are used at the final focus for secondary fragmentation reactions and Coulomb excitation respectively. The reaction products are selected using the calorimeter telescope array CATE [4], consisting of an array of 3×3 Si-CsI(Tl) ΔE-E telescopes. The energy loss in the Si detectors provides unambiguous Z identification after the secondary target. Due to the parallel momentum distribution in fragmentation processes, the total energy measurement of the fragments is however insufficient to completely distinguish masses. Position sensitivity of the Si detectors enables scattering angle determination. Since 2005 an additional thin position sensitive Si ΔE detector with a size of 5×5 cm^2 was placed directly after the secondary target. Together with the CATE Si ΔE detectors the fragment trajectories were determined with a position resolution of 3 mm in x and y.

The γ-rays emitted by the reaction products were measured in the in-flight experiments with 15 Cluster Ge detectors, containing 7 crystals each, positioned in three

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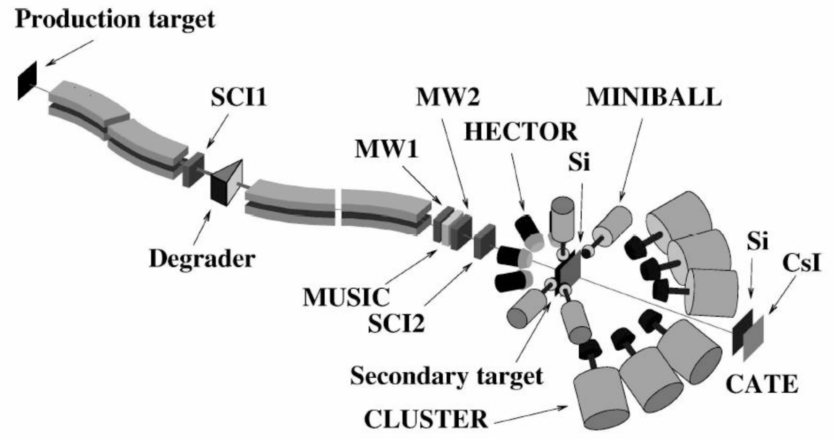

Fig. 1. Schematic of the RISING in-flight set-up.

rings at extreme forward angles of 16°, 33° and 36°. For some experiments up to 8 six-fold segmented MINIBALL triple Ge detectors were arranged in two rings with central angles of 45° and 85° relative to the beam line at forward angles. The full energy efficiency of this arrangement amounts to 3% for 1.3 MeV γ rays emitted at v/c = 0.5. In addition the HECTOR array [5], consisting of 8 large volume BaF2 detectors, was situated at angles of 85° and 142°. The position sensitivity of the MINIBALL detectors allowed them to be placed at a close target distance of 250 mm, while the Cluster and HECTOR detectors sat at larger distances of 700 mm and 300 mm, respectively. In order to obtain the best energy resolution for the γ-rays emitted in flight at velocities of v/c $\approx$ 0.5, excellent tracking of the moving nuclei is mandatory. Employing sophisticated analysis algorithms an energy resolution of $\leq$1.5% was achieved.

Relativistic Coulomb excitation was used in several experiments in order to extract absolute B(E2) values of the first excited state in unstable nuclei. In the isotopes ^{56}Cr and ^{58}Cr the results confirm the subshell closure at $N = 32$ which was already indicated by the excitation energy of the 2^+ state in ^{56}Cr [6]. The result presents a challenge for large scale shell model calculations which predict a much larger B(E2) value. In the ^{108}Sn isotope the obtained B(E2) value is in agreement with the theoretical calculations [7]. Secondary fragmentation reactions were used in several experiments to study proton rich unstable nuclei. Preliminary results on T = 3/2 mirror nuclei in the A $\sim$ 50 region show the potential power of this method [8].

The secondary 1n knock-out reaction was used to measure the energy of the first excited 2^+ state in ^{36}Ca which is the mirror nucleus of ^{36}S [9]. The excitation energy was found to be 276 keV lower than in the T = 2 mirror nucleus ^{36}S, indicating that a major part of the Coulomb energy difference is due to the Thomas-Ehrmann shift.

Besides the Coulomb excitation of the first excited 2^+ state, relativistic Coulomb excitation of ^{136}Nd at RISING allowed to populate also the second excited 2^+ state and to deduce three B(E2) values. Figure 2 shows the corresponding γ spectrum, demonstrating the high quality which can be achieved by optimal background reduction and Doppler correction in the analysis. The results confirm that this nucleus is indeed triaxial.

The decay spectroscopy programme of the RISING project is discussed in another contribution to this issue [10]. One finding of this on-going campaign opens an important perspective for in-beam experiments. By massive fragmentation of a ^{208}Pb beam on a Be target a 27^+ isomer was populated in the isotope ^{148}Tb [11]. The population of medium spin metastable states produced in relativistic-energy fragmentation of a ^{238}U beam has been observed previously already [12]. For states with angular momentum $\leq 20\hbar$, a much higher population than expected has been found. By introducing a collective component to the generation of angular momentum the experimental data can be understood. The new data support this interpretation and demonstrate convincingly that the high angular momentum part of the spin distribution in massive transfer can reach several percent. Therefore fragmentation reactions may be used for in-flight high spin spectroscopy, complementing classical fusion evaporation reactions which are not suited for neutron rich nuclei.

3 The AGATA Demonstrator

To fully exploit the exotic beams, lasting problems in detection efficiency have to be solved. They result from limited beam intensity, particularly for the most exotic nuclei, a wide range of beam velocities (from stopped to v/c $\sim$ 0.5), high γ ray and particle background and γ ray multiplicities up to M = 30, which are typical characteristics of the reactions. A 4π γ-ray array with highest efficiency, selectivity and energy resolution is required which is capable of high event rates. These features can only be achieved with a close packed arrangement of detectors. The individual interaction points of the γ quanta have to be determined by pulse shape analysis and disentangled by tracking algorithms. The Advanced GAmma Tracking Array, AGATA [3], will provide 25% to 40% full energy

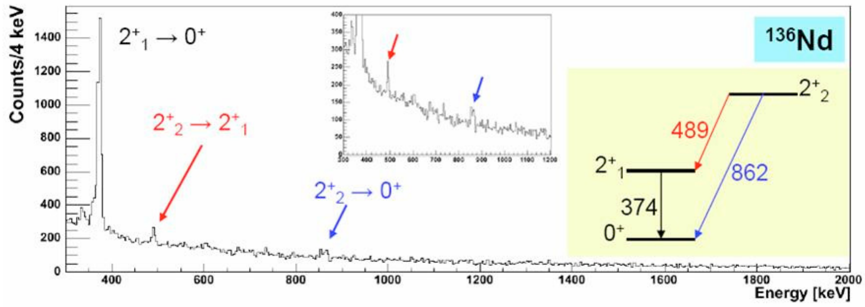

Fig. 2. Doppler corrected γ spectrum of ^{136}Nd after Coulomb excitation on Au.

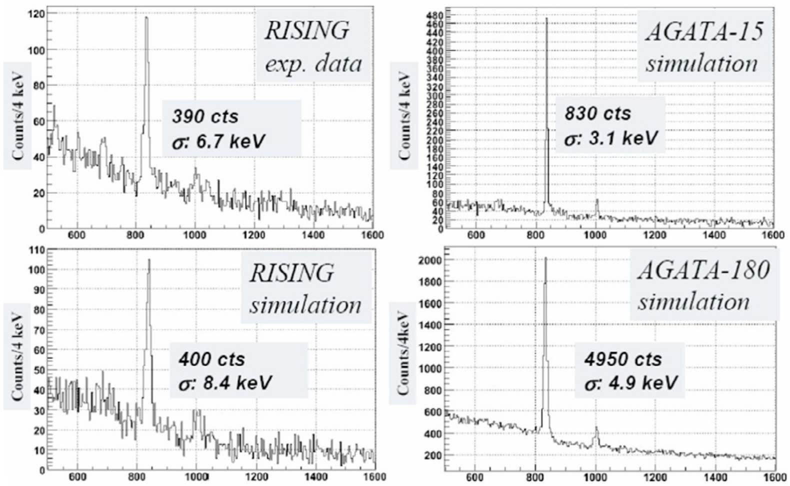

Fig. 3. Comparison of spectrum quality with RISING (left) and AGATA (right) (courtesy A. Bürger [13]).

efficiency depending on the γ multiplicity. The position resolution is sufficient for an energy resolution of 0.4% at a beam velocity of v/c = 0.5. The first AGATA detector unit even surpassed its design qualities in an in-beam experiment. Therefore planning of experimental campaigns employing AGATA detectors has started in accord with the advent of future RIB facilities.

For future γ ray detection at the SIS/FRS facility the AGATA Demonstrator array is proposed in conjunction with the Cluster Ge detectors used in RISING. The 15 detector elements of the AGATA sub-array placed at a distance of ca. 15 cm at forward angles already provide about 8% efficiency at 100 MeV/u. The position resolution of $<$5 mm ensures an energy resolution after Doppler correction of $\approx$0.4% at 100 MeV/u. Figure 3 shows the improvement of spectrum quality inferred from simulation calculations [13]. The 15 Cluster detectors are proposed to cover intermediate and backward angles. In a compact arrangement they will add 16% efficiency at a moderate 4% energy resolution. Combining both systems enables highly selective $\gamma\gamma$-coincidences to be measured in fragmentation reactions.

For the proposed campaign novel detectors emerging from FAIR/NUSTAR developments should become available. In particular it is planned to replace the MUSIC detector and one of the multi-wire chambers by Si strip detectors to increase the count rate capability at the final focal plane and reduce the energy straggling.

Experience from RISING plus CATE experiments shows that high-quality beam tracking and higher granularity at central angles is crucial to achieve optimal mass resolution. The inclusion of flight-time measurement is also essential, because the velocity uncertainty due to reaction mechanisms and slowing down processes in the secondary target prevent a clean mass identification solely based on ΔE/E information. Therefore, E_{tot}-ToF will be employed with a position sensitive ΔE/E calorimeter and fast scintillators. The set of detectors behind the target will be renewed completely within the LYCCA (Lund-York-Cologne CAlorimeter) project, initiated to upgrade RISING.

The efficiency as well as the energy resolution of the AGATA part of the proposed layout is almost three times higher then what is achieved with the current RISING set-up. The total efficiency including the Cluster detectors is even 24%! Keeping in mind the low to moderate multiplicities expected the gain in sensitivity and selectivity is substantial. Combining both systems enables e.g. for the first time highly selective $\gamma\gamma$-coincidences to be measured in fragmentation reactions. In addition, a suite of ancillary detectors which will be developed within FAIR/NUSTAR, may be used to further enhance the sensitivity and selectivity of the set-up.

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