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Exciting isomers from the first stopped-beam RISING campaign

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Abstract. First results are reported from a major new initiative of experiments, which focus on nuclear structure studies at extreme isospin values by means of isomer spectroscopy. The experiments represent the first part of the so-called stopped-beam campaign within the Rare ISotope INvestigations at GSI (RISING) project. Time-correlated γ decays from individually identified nuclear species have been measured, allowing the clean identification of isomeric decays in a wide range of exotic nuclei both at the proton drip-line and in heavy, neutron-rich systems. An overview of the experimental technique will be given, together with the performance of the new germanium detector array and future research plans for the collaboration.

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1 Introduction

A central topic in contemporary nuclear structure physics is the investigation of exotic nuclear matter far from the line of β stability. An important tool in these studies is γ-ray spectroscopy, providing valuable fingerprints of these exotic nuclei and, subsequently, revealing information on their internal structure. *Rare ISotope INvestigations at GSI* (RISING) combine the existing *FRagment Separator* (FRS) [1] – to discriminate radioactive nuclear beam species – with primarily fifteen high-efficiency CLUSTER germanium detectors [2] for γ-ray detection.

RISING started in 2003 with the so-called fast-beam campaign, within which exotic nuclei were studied by means of relativistic Coulomb excitation, secondary fragmentation, or knock-out reactions [3,4]. In late 2005 these experiments were followed by the g-RISING campaign aiming at the measurement of magnetic moments of isomeric states populated by either fragmentation reactions or relativistic fission of heavy primary beam particles. In the

Table 1. Summary of the main characteristics of the experiments performed within the passive-stopper part of the stopped-beam RISING campaign.

Focus	Aim	Primary Beam	Spokesperson	Date
^{86}Tc	$T = 0 - T = 1$ competition in heavy odd-odd $N = Z$ nuclei	^{107}Ag at 750 AMeV	P.H. Regan	02/06
^{204}Pt	Shell-structure south of ^{208}Pb	^{208}Pb at 1000 AMeV	Zs. Podolyák	02/06
^{54}Ni	Isospin symmetry and effective charges near ^{56}Ni	^{58}Ni at 550 AMeV	D. Rudolph	03/06
^{130}Cd	Search for the 8^+ $\pi(g_{9/2})^{-2}$ isomer in $N = 82$ ^{130}Cd	^{136}Xe at 700 AMeV	A. Jungclaus	06/06
^{130}Cd	Evolution of shell structure near ^{132}Sn	^{238}U at 650 AMeV	M. Górska & M. Pfützner	07/06
^{110}Zr	Dynamical symmetries in neutron-rich Zr isotopes	^{238}U at 750 AMeV	A.M. Bruce	12/06

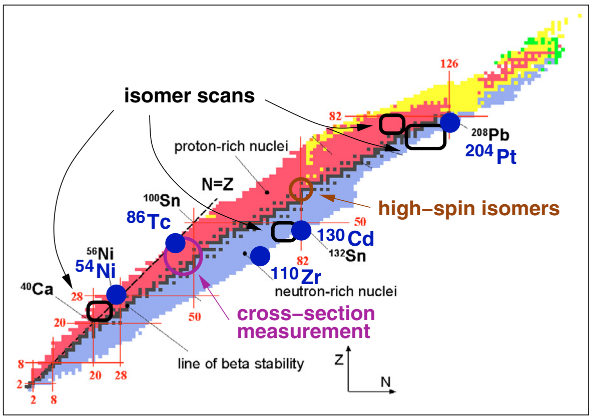

Fig. 1. Overview of the main aims and additional studies (to be) performed within the passive-stopper part of the stopped-beam RISING campaign. See also Table 1.

beginning of 2006 RISING was reconfigured once more to enable the so-called stopped-beam campaign. This campaign has two major incentives, namely (i) to identify and study electromagnetic decays of metastable, excited nuclear states, and (ii) measure γ rays following β decays to excited states into the daughter nuclei. In both cases, the nuclei are implanted and stopped in the center of the RISING array; either in a passive stopper material, such as metal or plastic plates, or in the future in an active stopper material in form of segmented silicon detectors.

This contribution focuses on a summary and some first results of the first passive-stopper, stopped-beam RISING campaign. More information is provided in [5,6].

2 Experiments

An overview of the topics and main characteristics of the RISING experiments within the passive-stopper, stopped-beam campaign is presented in Table 1 and figure 1. All six experiments aim at nuclei located at the present border of knowledge and yield for γ-ray spectroscopy. The two experiments on the neutron-deficient side of the nuclidic chart shall reveal information on isospin symmetry aspects of the effective nuclear force, while the four experiments on the neutron-rich side intend to probe the evolution of shell structure far from stability. These topics are mainly investigated by means of nuclei, which have few nucleon holes with respect to "classical", doubly-magic nuclei such as ^{56}Ni, ^{132}Sn, and ^{208}Pb.

The experiments performed so far have all been very succesful for the primary goals outlined above: The predicted isomeric states could be identified in ^{54}Ni, ^{86}Tc, ^{130}Cd, and ^{204}Pt. Furthermore, each experiment was able to allocate time for a number of secondary goals, which are also indicated in figure 1. For example, several surveys for new isomers were performed as well as cross-section measurements and quests for high-spin states populated in fragmentation reactions (cf. [5,6]).

The nuclei of interest were produced by either fragmentation reactions or relativistic fission of primary beams (cf. Table 1) provided by the SIS accelerator at GSI, Darmstadt, Germany. These beams hit beryllium targets of varying thicknesses between 1.0 and 4.0 g/cm^2. Subsequently, the reaction products were selected by means of a $B\rho - \mathit{\Delta} E - B\rho$ technique in the FRS [1]. The identification in terms of mass A and proton number Z of each transmitted ion is performed with a suite of detector elements placed at the intermediate S2 and final S4 focus of the FRS (cf. [6] for one specific example).

A photograph of the S4 set-up taken at the end of the first part of the campaign is provided in figure 2. It shows the respective detector elements as well as the RISING Ge-array. The secondary beam including the nuclear species of interest enters the picture at the bottom right. It first passes two multiwire chambers (MW41 and MW42) and two ionization chambers (MUSIC41 and MUSIC42). The multiwire chambers yield position and incident angle of the individual ions, while their differential energy loss in the ionization chambers provides their proton number, Z. The following scintillator SC41 provides both the trigger signal for the data acquisition, the start signal for the γ-ray timing, and the logic start signal of the time-of-flight measurement between S2 and S4, from which the mass-to-charge ratio A/Q of the ions can be derived. Note that $Q = Z$ for most of the experiments. The ions are then slowed down in an aluminum degrader with variable thickness to achieve proper implantion in a plastic, beryllium, or copper stopper "foil" (catcher). These have thicknesses of a few millimeters and are optimized for the respective experiment. The catcher is hidden in the center of the encircled RISING Ge-array in figure 2. Scintillation detectors SC42 and SC43 are placed before

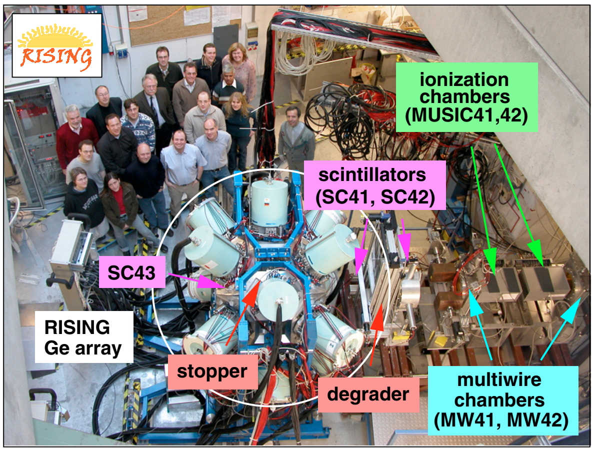

Fig. 2. Focal-plane set-up of the stopped-beam Rising campaign. See text for details.

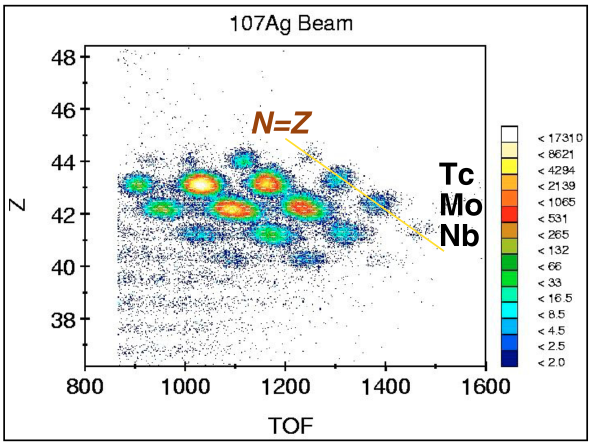

Fig. 3. Identification of isotopes reaching the S4 focal plane of the FRS for the ^{86}Tc setting.

and behind the catcher to allow for suppression of ions having been destroyed during the slowing down process or passing through the catcher, respectively, in the offline analysis.

The Rising Ge-array comprises fifteen Cluster germanium detectors [2], i.e., a total of 105 Ge crystals. In the stopped-beam configuration the Cluster detectors are arranged in three rings of five detectors at central angles of 51°, 90°, and 129° with respect to the secondary beam direction. The distance of the crystals from the center of the S4 focal plane amounts to ~21 cm. Hence, the array combines high efficiency with high granularity. Notably, the latter proved to be extremely important for dealing with the so-called "prompt flash", which is radiation emitted while the residues slow down in the catcher. Depending on reaction and secondary beam energy, only five to ten crystals were affected in a given event, and could thus not be used to detect isomeric γ-rays.

Another major step is the digital processing of energy and timing signals of the 105 Ge crystals using thirty 4-channel XIA Digital Gamma Finder (DGF) modules, i.e., two per Cluster. These modules include an internal 40 MHz clock, which allows for time stamping of the γ-ray events in steps of 25 ns. For time $t = 0$ reference, the SC41 trigger signal was also processed in three DGF channels. For both short-lived isomers and redundancy, a conventional timing branch is installed in parallel and digitized with a short-range ($t \leq 1\ \mu$s) and a long-range ($t \leq 0.8$ ms) VME TDC. If the isomer survives the 150–200 ns flight time through the FRS, the γ-ray set-up was sensitive to isomeric decays in the range of about 10 ns to 1 ms. See [5] for more information on these issues.

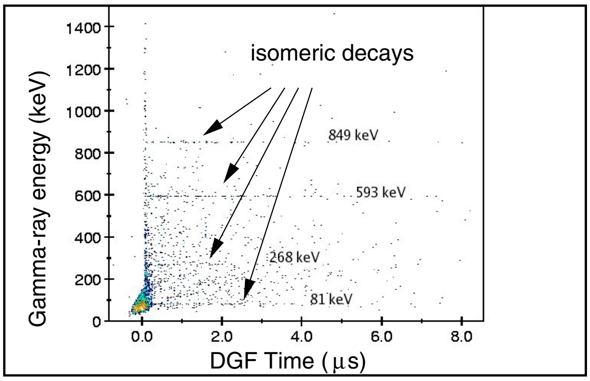

Fig. 4. Correlation matrix between γ-ray energies and times following implantations of ^{86}Tc in the stopper. Time zero of the implantation is given by the intense, vertical line at channel number ≈ 1008. Delayed γ-ray transition are seen as horizontal lines fading out towards longer and longer times.

3 First results

The first step in the analysis aims at event-by-event isotope identification of the secondary beam particles. Figure 3 provides a typical example, taken from the very first experiment within the campaign. A number of Nb, Mo, and Tc isotopes can be discriminated in a scatter plot of Z determined from the ionization chambers vs. time-of-flight (TOF) between the S2 and S4 areas. Here, the focus lies on the odd-odd $N = Z$ nuclei ^{86}Tc [7] and ^{82}Nb.

For a selected isotope, the next step implies the construction of a correlation matrix between γ-ray energy and (delayed) time of its observation relative to the implantation of the ions in the catcher. This is illustrated in figure 4 for the case of ^{86}Tc. The vertical line on the left hand side marks the "prompt flash", i.e., implantation time $t = 0$, while fading, horizontal lines (here: $E_\gamma = 81$, 268, 593, and 849 keV) indicate decays from isomeric states.

The preliminary results for ^{82}Nb and ^{86}Tc include good candidates for the 2^+ $T = 1$ isobaric analogue states of ^{82}Zr and ^{86}Mo, respectively, while the observed isomeric states most likely have negative parity, which is in line with available Nilsson orbitals close to the Fermi surface [8,9]. The final results will thus probe fundamental isospin $T = 0$ and $T = 1$ competition (cf. [10–12]).

Starting from isotope selected γ-ray energy-time correlations as displayed in figure 4, time spectra can be produced for selected γ rays, which are then used to derive the

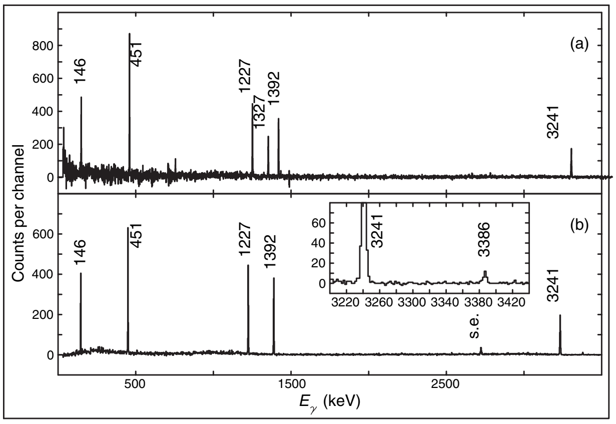

Fig. 5. Panel (a) provides a γ-ray singles spectrum in the time range 0.05 μs $\leq t \leq$ 1.0 μs following the implantation of ^{54}Ni ions in the stopper. Panel (b) is a $\gamma\gamma$ correlation spectrum in coincidence with one of the 451, 1227, or 1392 keV transitions in ^{54}Ni. The same timing conditions as for panel (a) were applied, but the FRS gates were less restrictive.

half-lives of the isomers. In turn, clean γ-ray energy spectra and, provided there is sufficient statistics, $\gamma\gamma$ correlation matrices can be produced by choosing proper timing windows. This is illustrated in the case of ^{54}Ni in figure 5. The top spectrum reveals six delayed γ-ray transitions at 146, 451, 1227, 1327, 1392, and 3241 keV, all having the same lifetime of $\tau \sim 220$ ns. Note that the 451, 1227, and 1392 keV lines are known to belong to ^{54}Ni, representing the $6^+ \to 4^+ \to 2^+ \to 0^+$ cascade in that nucleus [13–15]. The 146 and 3241 keV lines are suggested to be the $10^+ \to 8^+$ and $8^+ \to 6^+$ transitions, at first based on mirror symmetry to ^{54}Fe, which has a well established isomeric 10^+ state with $\tau = 525(10)$ ns [16]. More reliably, they are found in coincidence with the known cascade, which is proven by figure 5(b). Here, another weak but distinct line can be discriminated at 3386 keV, which marks the $10^+ \to 6^+$ $E4$ branch of the isomeric decay in ^{54}Ni.

Interestingly, the 1327 keV line seen clearly in figure 5(a) is absent in figure 5(b). Since it exhibits (within uncertainties) the same half-life as the other transitions and because it fits in energy, we associate it with the $9/2^- \to 7/2^-$ ground-state transition in ^{53}Co. The $9/2^-$ state in ^{53}Co can be populated with a direct proton decay of 1.28 MeV from the 10^+ isomer in ^{54}Ni. This would be the first (indirect) evidence for proton emission following a fragmentation reaction and bring the associated research field back to its roots, since direct proton decay was first observed in ^{53m}Co in 1970 [17].

4 Summary and outlook

To summarize, the first part of the RISING stopped-beam campaign was highly succesful by discriminating in part long-sought isomeric states in ^{54}Ni, ^{82}Nb, ^{86}Tc, ^{130}Cd, and ^{204}Pt. As an unexpected highlight, the first proton-emitting state following fragmentation reactions could be established in ^{54}Ni. In addition, the data comprise isomeric states in numerous neutron-deficient and neutron-rich nuclei, which will allow for detailed and systematic investigations of the fragmentation and relativistic fission processes, mainly by means of isomeric ratios (cf. [18] and Refs. therein). Here, the observation of an isomeric 27^+ state in ^{148}Tb sets a new high-spin world record for fragmentation reactions (cf. [6]).

At present (August 2006), the passive-stopper part is envisaged to be followed by a series of active-stopper experiments in 2007. These include isospin symmetry tests by means of comparing Gamow-Teller strengths derived from β decay and charge-exchange reactions, related proton-neutron pairing effects on β decay beyond $N = Z$, studies of the evolution of collectivity south of ^{208}Pb, and, last but not least, a revisit of the ^{100}Sn region.

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