First Results from the Stopped RISING Campaign at GSI: The Mapping of Isomeric Decays in Highly Exotic Nuclei

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Abstract. The first results from the Stopped Beam RISING experimental campaign performed at the GSI laboratory in Darmstadt, Germany, are presented. RISING (*Rare ISotope INvestigations at GSI*) constitutes a major new experimental program in European nuclear structure physics research aimed at using relativistic-energy, projectile-fragmentation reactions to study nuclei with exotic proton-to-neutron ratios. This paper introduces the physics aims of the Stopped RISING collaboration and presents some technical details and initial results from experiments using the RISING array to study decays from metastable nuclear states in both proton and neutron-rich nuclei.

Keywords: Gamma-ray spectroscopy; nuclear isomers; nuclear structure; nuclear level lifetimes.
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INTRODUCTION

The study of the internal structure of atomic nuclei with exotic proton to neutron ratios has become a main thrust of nuclear physics research worldwide [1]. This interest has led to the development of radioactive beam facilities which allow the production and study of nuclei species of specific elements as radioactive beams of nuclei [2]. Two main techniques are used for such work, namely (i) Isotope Separation On Line and (ii) Projectile Fragmentation/Fission. In the latter, fast beams traveling at speeds greater than the Fermi velocity (i.e. typically with energies greater than 50 MeV per nucleon) are used to induce reactions on thick stationary targets. Large magnetic separators such as the GSI Fragment Separator (FRS) [3,4] can then be used to both select and identify the exotic secondary species of interest using magnetic rigidity, time of flight and energy loss measurements. Such high-energy collisions produce a plethora of residual nuclei following a two step process of abrasion (i.e., the initial removal of nucleons from the beam nucleus) and a ablation (i.e. the evaporation of subsequent light particles as the hot initial fragment cools down) [5]. This paper reports on the first results of the Stopped RISING collaboration, aimed at investigating the structure of exotic nuclei following their production in projectile fragmentation reactions at GSI.

THE RISING PROJECT

RISING is the acronym for 'Rare Isotope INvestigations at GSI' and involves the use of high-efficiency germanium CLUSTER detectors [6] for nuclear spectroscopy studies using projectile fragmentation beams.

The Stopped Beam RISING Project

The Stopped Beam RISING project is aimed at utilizing the combined power of a highly modular γ-ray spectrometer with the selection power of the FRS to identify decays from (i) metastable states in and/or (ii) following the β-decay of the exotic nuclei. The use of projectile fragmentation reactions to study decays from metastable states was pioneered in experiments at the GANIL laboratory using intermediate energy beams [8-10]. Subsequent work using higher energy beams approaching 1 GeV per nucleon has been carried at GSI using heavy beams such as ^{208}Pb [11-15] and ^{238}U [16-18]. A significant part of the Stopped Beam RISING Campaign is aimed at building on these previous experiments in order investigate the limits of nuclear isomer spectroscopy.

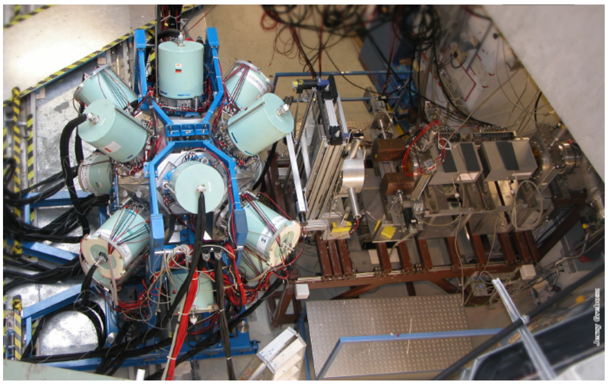

FIGURE 1. Photograph of the RISING array in its Stopped Beam configuration. To the right of the array are the variable thickness aluminum degrader together with various scintillators and ionization chambers used to provide the time of flight, position and energy loss information to identify the fragmentation residues event-by-event.

Figure 1 shows a photograph of the RISING array in its Stopped Beam configuration. The beam-line elements directly to the right of the array include a variable width aluminum energy degrader (which allows the experimenters to vary the energy of the incoming secondary ions such that they can be tuned to stop in the passive stopper placed in the center of the RISING array. In its Stopped RISING configuration RISING consists of fifteen, seven-element germanium cluster detectors [6], placed in three rings of five detectors centered at 51°, 90° and 129° to the secondary beam axis. The detectors are placed approximately 22 cm from the center of the final focal plane of the GSI Fragment Separator. The photopeak γ-ray efficiency measured in the center of a 7 mm thick plastic passive stopper placed in the focal plane was measured to be 14(1)% at 661 keV and 9(1)% at 1332 keV for 102 working crystals (note these values are without Compton add-back between neighboring detectors).

One of the major innovations utilized in the initial Stopped Beam RISING experiments was the use of digital electronics to process both the energy and timing signals from the germanium detectors. These were instrumented using 4-fold DGF ('Digital Gamma Finder') modules similar to those described in [19]. These modules incorporate a free running internal clock with an intrinsic 25ns timing stamp associated with each γ-ray event. This enables excellent correlation to be determined between specific ions implanted in the passive stopper placed in the center of the FRS final focal plane and any subsequent decay from isomeric states with half-lives in the 10ns to 1ms range.

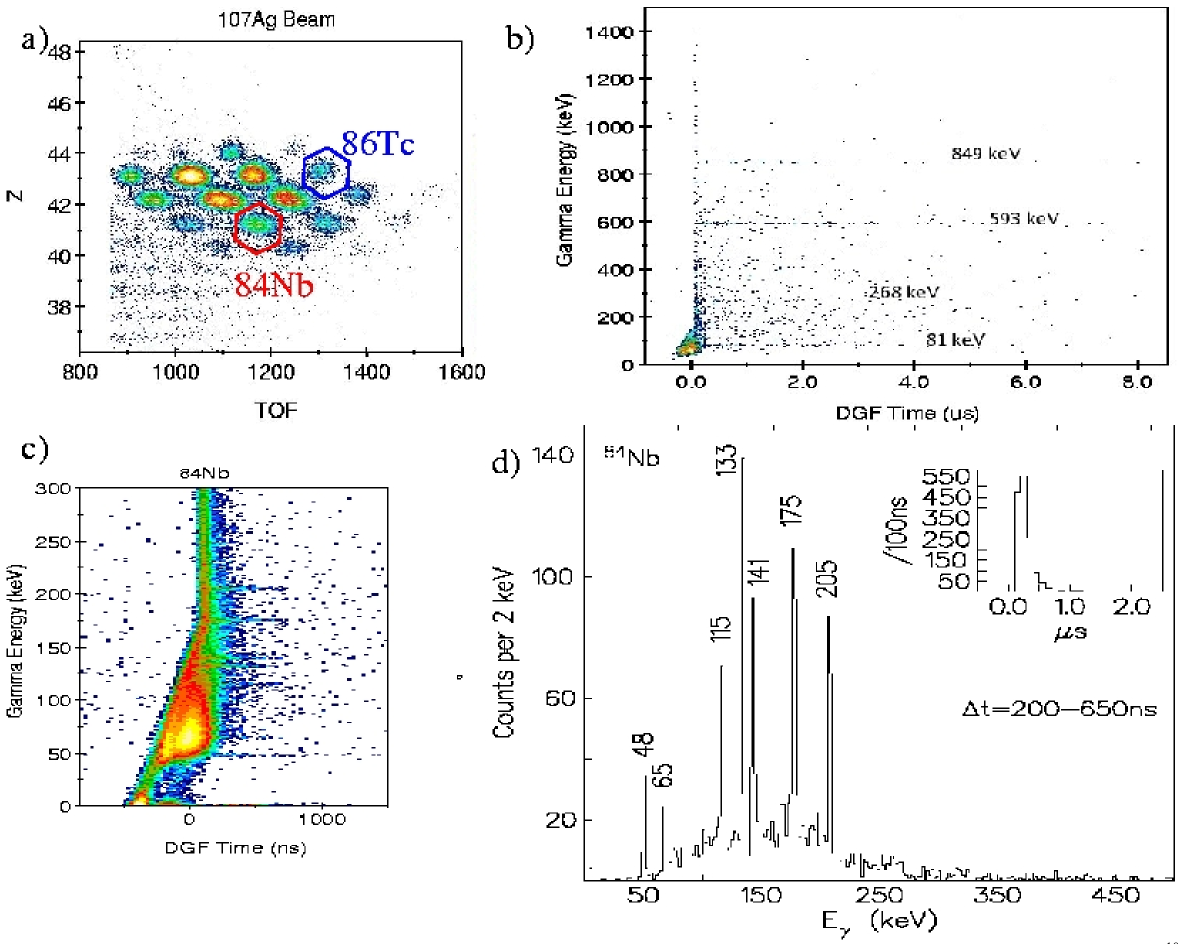

FIGURE 2. Selection of results associated with the Stopped RISING experiment using the projectile fragmentation of a ^{107}Ag primary beam to study isomeric states in N~Z nuclei. (a) Particle identification plot showing Z (deduced from the particle energy loss) and time of flight through the FRS. Those ions identified with ^{86}Tc and ^{84}Nb are highlighted using the hexagons. (b) 2-D matrix of measured γ-ray energy in the RISING detectors versus time of detection after ion implantation in the stopper as measured using the digital clock on the DGF modules. (c) Same as (b) but gated on ^{84}Nb ions. (d) transitions below the previously reported isomer in ^{84}Nb [20] from γ-ray and time projections of cuts on the matrix in figure (c)

Experimental Examples

The first two initial experiments performed as part of the Stopped RISING campaign were studies using the projectile fragmentation of: (i) a 750 MeV/*u* ^{107}Ag and (ii) 1 GeV/*u* ^{208}Pb beam to study (i) isospin symmetry and proton-neutron pairing effects and (ii) the role of proton-hole excitations in the doubly magic ^{208}Pb core and the robustness of the N=126 shell closure in neutron-rich nuclei respectively. Figure 2 shows examples of the raw particle identification spectra produced in the study of the N=Z=43 nucleus, ^{86}Tc using the ^{107}Ag primary beam. By selecting specific species, previously reported isomeric decays associated with neighboring nuclei such as ^{84}Nb [20] can be selected. Two-dimensional matrices of γ-ray energy versus decay time after implantation can then be created for each individual nuclear species.

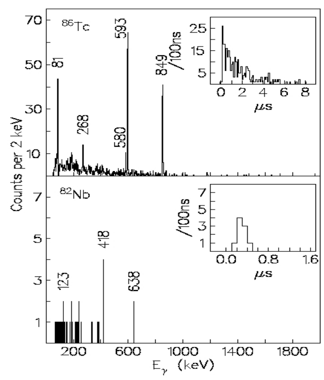

FIGURE 3. Delayed γ-ray energy and time spectra associated with isomers in the N=Z nuclei ^{86}Tc (upper) and ^{82}Nb (lower) following the fragmentation of a ^{107}Ag beam.

By making cuts on these 2-D arrays, energy and time spectra can be cleanly resolved. The low-energy response of the array in the Stopped RISING configuration is demonstrated by the observation of the 48 and 65keV lines in ^{84}Nb (see figs 2c and 2d). Figure 3 confirms the previously reported isomer in ^{86}Tc [10] and an isomer is identified for the first time in the N=Z=41 system, ^{82}Nb. Figure 4 shows the previously reported isomers in the N=126 nucleus ^{206}Hg [21] associated with a low-lying $I^{\pi}=5^{-}$, two-proton hole excitation and a higher-lying maximally aligned $I^{\pi}=10^{+}$ $(\pi h_{11/2})^{-2}$ configuration. Similar decays are observed in the N=126 isotone ^{204}Pt for the first time in this work. The enhanced population of high-*j* seniority states in 'knockout' reactions has recently been proposed as a potential mechanism for the study of even more exotic neutron-rich systems [22].

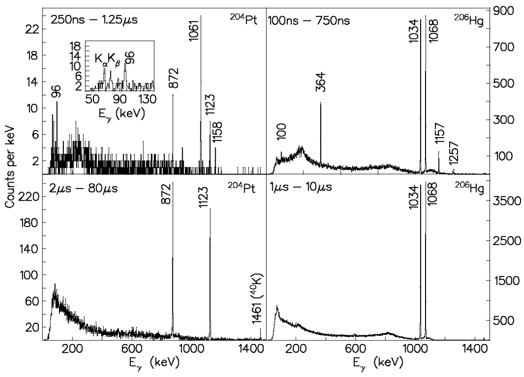

FIGURE 4. Delayed γ-ray spectra associated with isomeric decays in the N=126 isotones ^{204}Pt and ^{206}Hg [21].

Figure 5 shows the previously reported isomers in ^{147}Gd [23] and ^{148}Tb [24] populated following the fragmentation of the ^{208}Pb beam. The isomer in ^{148}Tb represents the highest discrete spin (27ħ) observed to date using projectile fragmentation reactions. This demonstrates the prospects for future high-spin studies with this method, particularly in neutron-rich nuclides inaccessible with stable beam/target fusion reactions.

Future Plans and Related Work

RISING Isomer experiments have also been performed using ^{58}Ni, ^{136}Xe and ^{238}U primary beams. Highlights include the identification of core breaking isomers in the ^{54}Fe/^{54}Ni mirror pair and new shell model isomers close to the ^{132}Sn doubly magic core. Future plans include the use of fission fragments for studies of neutron-rich A~110-130 nuclei and the implementation of a segmented silicon 'active stopper' for β-delayed spectroscopy. Initial experiments to measure β-decay half-lives have provided promising results for this future stage of the project [25].

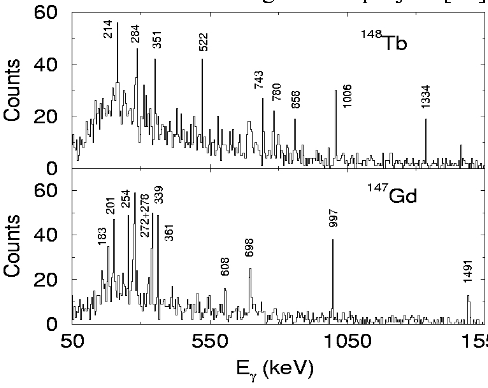

FIGURE 5. Delayed γ-ray spectra associated with the high-spin isomers in ^{148}Tb and ^{147}Gd from the ^{208}Pb experiment.

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