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Isomer Spectroscopy Using Relativistic Projectile Fragmentation at the N=Z Line for A∼80→90.*

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The preliminary results from the RISING Stopped Beam Isomer Campaign are presented, with specific focus on results of the initial experiment to investigate isomeric decays along the N=Z line around A∼80-90 following the projectile fragmentation of a ^{107}Ag primary beam at an energy of 750 MeV per nucleon. A description of the technical aspects behind the design of the RISING array is presented, together with evidence for previously unreported isomeric decays in ^{87,88}Tc and the N=Z nuclei $^{82}_{41}$Nb and $^{86}_{43}$Tc.

1. INTRODUCTION

The use of projectile fragmentation reactions as a tool to populate and study the structural properties of nuclei with exotic proton-to-neutron ratios has become widespread over the last decade. Specifically, isomeric decays from states with lifetimes ranging from tens of nanoseconds to milliseconds have been studied using the fragmentation process at both intermediate (see e.g. [1–5]) and relativistic (e.g., [6–13]) energies. RISING is the acronym for 'Rare ISotope INvestigations at GSI' and constitutes a major experimental programme in European nuclear structure physics research, aimed at using relativistic energy (typically 500→1000 MeV per nucleon) projectile fragmentation reactions to populate nuclei with highly exotic proton-to-neutron ratios compared to those on the line of beta stability. RISING consists of fifteen, seven element 'cluster' germanium detectors [14], which were formerly part of the EUROBALL gamma-ray array. The RISING array can be coupled to the Fragment Separator (FRS) [15] at GSI in order to observe decays from excited states in exotic nuclei formed following projectile fragmentation and fission at relativistic energies.

This paper describes results from the subsequent 'Stopped Beam' campaign using the RISING detectors to study decays from isomeric states. (Details of the 'in-beam' phase of the RISING project, the so-called 'Fast-Beam' campaign, can be found in reference [16].) In its high-efficiency Stopped Beam configuration, the RISING gamma-ray spectrometer consists of 105 individual, large volume germanium crystals that view a focal plane in which the exotic nuclei are brought to rest (i.e. 'stopped'). Here, decays from metastable excited states with half-lives in the nano-to milliseconds range can be observed, often providing the first spectroscopic information on these exotic nuclear species. This paper introduces the physics aims of the Stopped RISING collaboration and presents some technical details on the RISING detector array. Results from one of the initial commissioning experiments are also shown and details of the planned future experimental program are given.

2. Experimental Details and Particle Identification Techniques.

The RISING array in its Stopped Beam configuration comprises 15, seven-element germanium cluster detectors in a high-efficiency configuration (see figure 1). The detectors were placed in three angular rings at 51, 90 and 129 degrees to the secondary beam axis,

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each containing 5 cluster detectors. The average distance from the front face of the detectors to the centre of the passive stopper at the final focal plane was approximately 22 cm. The measured photopeak γ-ray efficiency for the array in this geometry for sources placed in the centre of the focal plane was approximately 15% at 661 keV.

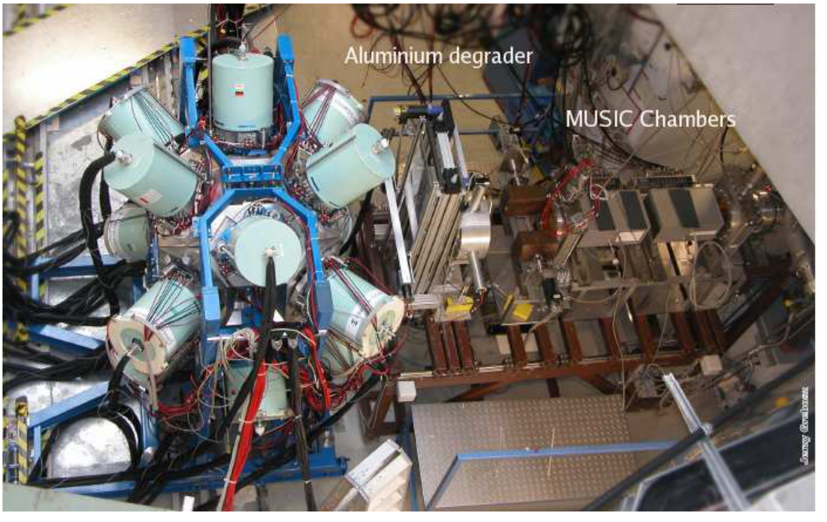

Figure 1. Photograph of the RISING gamma-ray array in its Stopped Beam configuration showing the aluiminium degrader and MUSIC energy loss detectors. The secondary beam enters from the right hand side of this picture.

The first experiment using the RISING array in its stopped beam configuration was aimed at the investigation of nuclear structure along the N=Z line approaching ^{100}Sn. Specifically, the aim was to use decays from isomeric states to populate and study the internal decays in the N=Z nuclei ^{82}Nb and ^{86}Tc in order to shed light on the competing roles of T=1 and T=0 proton-neutron pairing in atomic nuclei [17].

The nuclei of interest in the first commissioning experiment were populated following the projectile fragmentation of a ^{107}Ag primary beam at an energy of 750 MeV per nucleon. The beam impinged on a 4 g/cm^2 beryllium production target with a typical intensity of $1\rightarrow3\times10^9$ particles per extraction spill. The SIS extraction spill lengths used for the ^{86}Tc production runs were typically $5\rightarrow6$ seconds over a total cycle time of 10 seconds. Standard time of flight, position and energy loss parameters were used to provide unambiguous particle identification through the FRS. At the end of the FRS, the ions passed through a variable thickness aluminium degrader (as shown directly to the right of the gamma-ray array in figure 1) such that the ions of interest came to rest in a passive stopper placed in the centre of the RISING array. In this experiment, the stopper was made from a multi-layered perspex block of total thickness 7 mm. Delayed gamma-rays were then detected using the RISING array. Each detected gamma-ray was time-stamped using a 40MHz clock as part of the DGF4 timing and energy signal processing [18]. More detail of the electronics and signal processing for the Stopped RISING array can be found in reference [19].

3. Experimental Results

Figure 2 shows the calibrated particle identification spectrum centred on ^{86}Tc ions following the ^{107}Ag projectile fragmentation. Figure 3 shows a two-dimensional calibrated matrix of delayed gamma-ray energy versus time after implantation in the perspex stopper, gated on the condition that clean, ^{86}Tc ions were identified in the event.

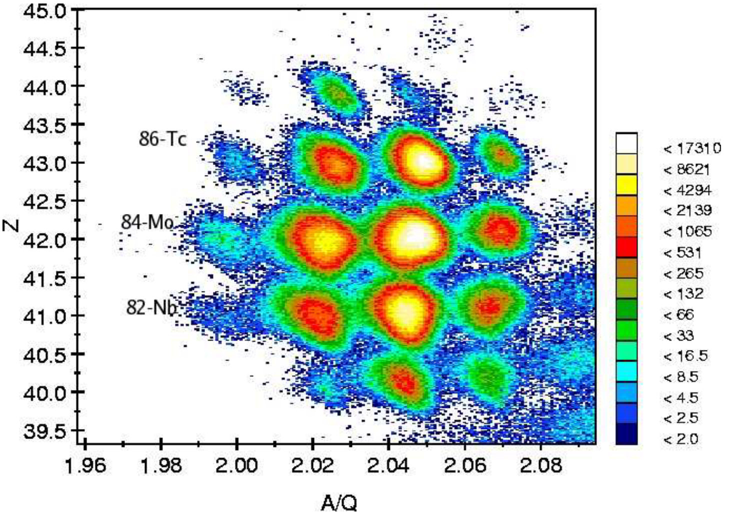

Figure 2. Calibrated particle identification spectrum centred on the N=Z line following the fragmentation of a ^{107}Ag beam. The atomic number and $\frac{A}{Q}$ parameters were derived event-by-event using time of flight, position, magnetic rigidity and energy loss parameters for the ions as they passed through the GSI Fragment Separator.

Figure 4 shows a projection of the ^{86}Tc gamma-ray energy versus time matrix shown in figure 3 and clearly identifies transitions associated with internal, isomeric decays in this N=Z=43 nucleus. The transitions at 593 keV and 849 keV are consistent with the lines assigned to this nucleus in our previous work [2,3]. The gamma rays at 593 keV, 849 keV and 81 keV are also shown to be in mutual coincidence following a gamma-gamma coincidence analysis on the current data when gated on ^{86}Tc ions. The ability to perform gamma-gamma coincidence analyses in such exotic nuclei provides a striking example of the resolving power provided by the high efficiency, high-granularity RISING array in its Stopped Beam configuration. Figure 4 also shows previously unreported transitions following isomeric decays in ^{87,88}Tc. (The published data to date on these nuclei come from

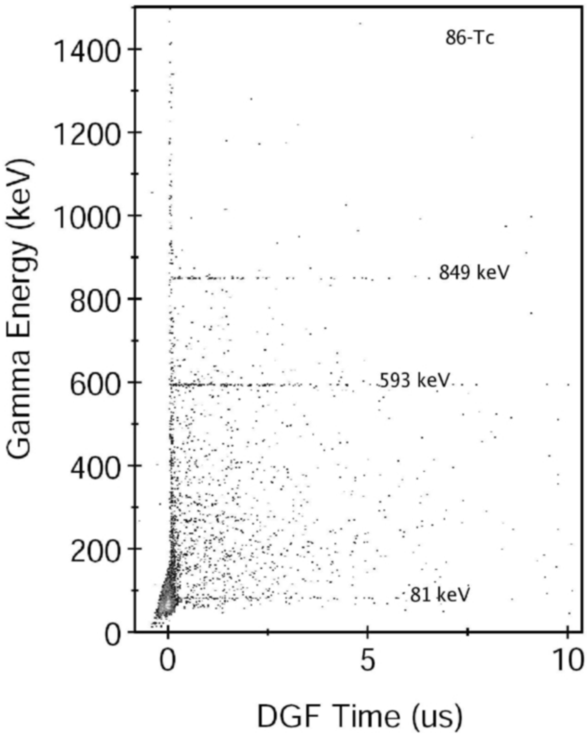

Figure 3. Two dimensional matrix of gamma-ray energy versus time after implantation (as measured using the DGF timing), gated on ^{86}Tc ions produced following the fragmentation of a ^{107}Ag beam at an energy of 750 MeV/u.

in-beam studies using the recoil-separator technique [23] and as such, were not sensitive to decays from isomeric states in the 100ns to few μs regime.)

In addition to the Tc isotopes, figure 4 shows delayed gamma-ray spectra associated with decays from isomeric states in the niobium isotopes ^{82,84}Nb. The isomer in ^{84}Nb has previously been reported [3,24]; its observation in the current work highlights the excellent low-energy efficiency response of the Stopped RISING array using the DGF timing electronics [18,19]. The transitions associated with the N=Z=41 nucleus ^{82}Nb are reported for the first time following this experiment. (Extended details of the analysis on this isotope can be found in reference [25].) We note that our previous work on this nucleus reported evidence for an isomer with a half-life in the hundred nanoseconds regime but could not confirm any discrete lines [3]. As in the case of ^{86}Tc, ^{82}Nb is the most neutron-deficient particle-bound isotope of this element [20] and is therefore located right at the proton drip line. The similarity of the transition energies at 418 and 638 keV to those decaying from the first two excited states reported in the $T_z = +1$ isobar, $^{82}_{40}$Zr at 407 keV and 634 keV [26], strongly suggest that the transitions observed in ^{82}Nb are

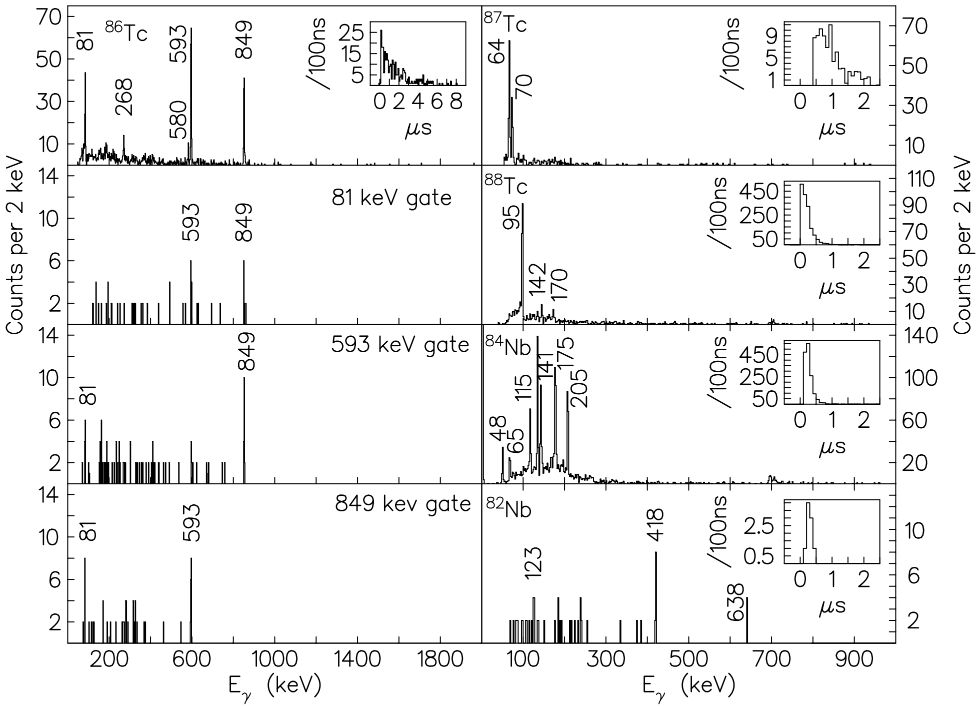

Figure 4. Gamma-ray and DGF time spectra associated with decays from isomeric states populated following the projectile fragmentation of ^{107}Ag at an energy of 750 MeV/u. (Left) Singles and $\gamma - \gamma$ coincidence spectra associated with the microsecond isomeric decay in ^{86}Tc as observed in the current work. (Right) Singles spectra showing the gamma-ray transitions and associated decay curves for isomeric decays in ^{87,88}Tc and ^{82,84}Nb as observed in the current work. See text for details.

decays from states built on the T=1, I^{π}=0$^+$ ground-state structure [21,22] in ^{82}Nb.

Figure 5 shows the excitation energies of the first $I^{\pi} = 2^+$, T=1 states in N=Z nuclei between $^{58}_{29}$Cu and $^{88}_{44}$Ru. The data points associated with $^{82}_{41}$Nb and $^{86}_{43}$Tc as observed in the current work appear to fit the systematics of these energies. The low-energy nature of the $I^{\pi} = 2^+$ excitation energy associated with the newly observed 418 keV transition in ^{82}Nb suggests a large deformation for this nucleus [28].

4. Other Stopped Beam RISING Experiments and Future Prospects

In addition to the preliminary analysis presented in the current paper, RISING isomer studies have also been performed using ^{58}Ni, ^{136}Xe, ^{208}Pb and ^{238}U primary beams. Highlights from these experiments include the identification of core breaking isomers in

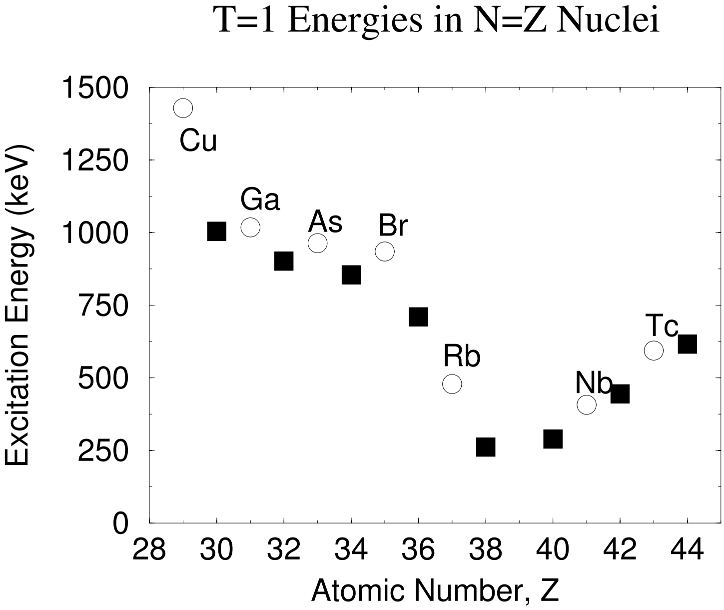

Figure 5. Excitation energy of the lowest T=1, $I^{\pi} = 2^{+}$ states in N=Z nuclei between Cu (Z=29) and Ru (Z=44). Data are taken from [32–41]. The data corresponding to even-even N=Z nuclei are represented by the filled squares with the empty circles representing the odd-odd N=Z systems.

the ^{54}Fe/^{54}Ni mirror pair [29] plus new shell model isomers corresponding to proton hole excitations in the ^{132}Sn [30] and ^{208}Pb [31] doubly magic cores. Future plans include the use of fission fragments for studies of neutron-rich A≈110→130 nuclei following production via projectile fission reactions 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 [42].

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