Vol. 38 (2007) ACTA PHYSICA POLONICA B No 4

FIRST RESULTS FROM THE STOPPED BEAM ISOMER RISING CAMPAIGN AT GSI*

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(Received November 19, 2006)

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[*] Presented at the Zakopane Conference on Nuclear Physics, September 4–10, 2006, Zakopane, Poland.

The first results from a series of experiments focused on the study of the internal structure of nuclei at the extremes of $N{:}Z$ ratio using isomer spectroscopy are reported. These experiments represent the first of the Stopped Beam section of the *Rare Isotopes Investigations at GSI* (RISING) project. Exotic nuclei were synthesized using relativistic projectile fragmentation of $\sim 500 \rightarrow 1000$ MeV/u beams of ^{107}Ag, ^{208}Pb, ^{136}Xe and ^{58}Ni, or fission of 750 MeV/u ^{238}U provided by the SIS synchrotron at GSI. A detailed description of the RISING stopped beam set up is given, together with a report of the performance of the associated gamma-ray spectrometer array. Selected results of the first experimental campaign are presented together with a discussion on the use of isomeric spectroscopy to study GeV range nuclear fragmentation. Details on future research plans of this collaboration are also outlined.

PACS numbers: 21.10.Tg, 23.20.–g, 25.70.Mn, 29.30.Kv

1. Introduction

The aim of the RISING (Rare ISotope INvestigations at GSI) collaboration is to use GeV range beams from the GSI/SIS synchrotron to study exotic nuclei produced through fragmentation. This production technique, coupled to a powerful germanium array from the decommissioned Euroball IV setup, plus the use of the FRS fragment separator for the selection and identification of the produced ions makes a powerful tool for the study of such nuclei. To date, two types of experiments have been conducted, the first campaign used the RISING fast beam setup [1] aimed at two-step fragmentation and/or relativistic Coulomb excitation studies. A review of these experiments can be found in [2]. The two other RISING setups used "stopped beam", either for isomer delayed γ-ray spectroscopy, which is the subject of this paper or for g-factor measurements [3]. The RISING setup moved to the Stopped Beam isomer spectroscopy configuration for the first time in February 2006. In this configuration the 105 germanium crystals of the RISING array (Fig. 1) are placed in a compact configuration around the final focal point of the FRS where they surround a passive stopper made of either perpex, copper or beryllium [4, 5]. Gamma-ray transitions depopulating isomeric states can then be observed using the fragmentation isomer spectroscopy technique as outlined in references [6–10]. Two experimental campaigns have been performed to date, aimed at studying specific physics including *(i)* evolution of shell closures around doubly magic nuclei and *(ii)* $N = Z$ symmetries. The current paper presents a description of the technical aspects of this setup as well as examples of the experimental performance of the γ-ray array. The use of microsecond isomer spectroscopy as a general tool to study the nuclear fragmentation process is also discussed.

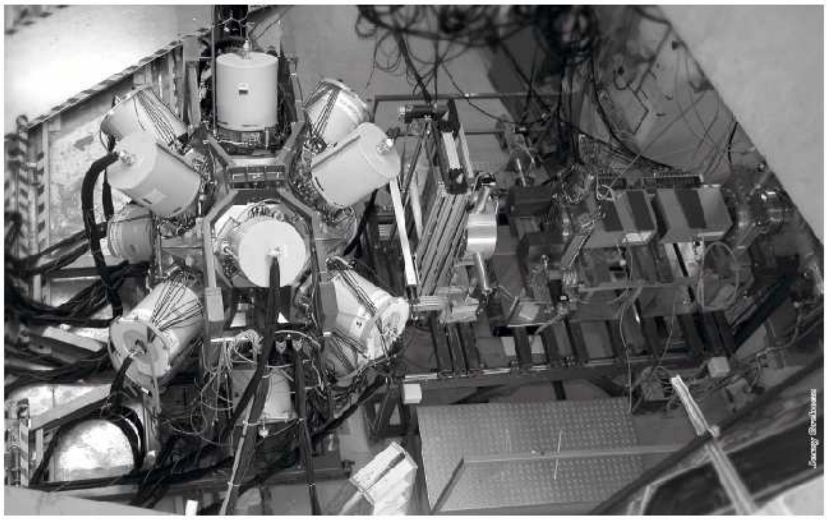

Fig. 1. Photograph of the RISING Stopped Beam γ-ray spectrometer.

2. Technical details

2.1. Production and identification of the exotic nuclei

Exotic secondary beams were produced using the projectile fragmentation of high-energy primary beams from the SIS synchrotron at GSI, incident on $1 \rightarrow 4$ g/cm^2 thick ^{9}Be production targets. The FRagment Separator (FRS) [11] was used in achromatic mode for the selection and identification of the reaction products using a standard time of flight and energy loss techniques [12]. Particle identification was achieved by the use of position-sensitive plastic scintillators at the middle and final focal points of the FRS to define the magnetic rigidities and velocities of the secondary ions. MUlti Sampling Ionization Chambers (MUSIC) before the final focus of the FRS provided energy loss signals from which the electric charge of the incoming ion could be deduced. Further details of the particle identification procedure can be found in [10]. An example from the RISING stopped beam experiment with ^{107}Ag primary beam is shown in Fig. 2. It should be noted that the achromatic degrader at the central focal point of the FRS was also used as a passive energy-loss device for charge state separation. The difference in magnetic rigidity between the first and second stage of the fragment separator can be used to estimate the energy loss of the ion through the achromatic degrader. This information together with the energy loss of the ions as measured at the final focal point using MUSIC detectors allows a unambiguous charge state discrimination. This technique is of particular interest in case of heavy, neutron-rich nuclei (see reference [13] for more details). As noted in reference [14], for high-Z nuclei this method of charge state selection can only be achieved for high-Z nuclei with energies greater than 300 MeV per nucleon. Thus the RISING setup at GSI is ideal for spectroscopic studies in such heavy, neutron-rich systems produced following relativistic projectile fragmentation reactions.

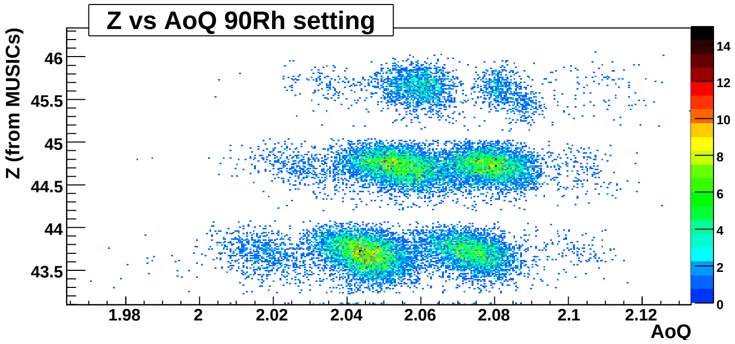

Fig. 2. Typical identification plot from the ^{107}Ag primary beam experiment. This setting was centered on the transmission of fully stripped $^{90}_{45}$Rh ions.

2.2. *The stopped RISING germanium array, geometry and electronics*

In its Stopped Beam configuration the RISING array comprises fifteen, seven-element germanium cluster detectors [15] from the former Euroball IV array. The detectors were placed in three angular rings of five detectors at 51°, 90° and 129° to the primary beam axis at an average distance from the centre of the array of approximately 22 cm. Each individual germanium detector had two parallel pre-amplifier outputs which were sent to two separate branches of the data acquisition. One was a fully 'digital' branch and provided the input signal for 105 channels within 30 Digital Gamma Finder (DGF-4C) modules [16]. Three parallel CAMAC crates, each holding ten, quad-input modules were used for this part of the electronics. The individual DGF channel triggers were validated by a master trigger signal generated from a fast plastic scintillator detector at the final FRS focal point. This signal was sent to a DGF channel in each crate in order to provide an internal check of the synchronization of the DGF clocks and also to provide a time-difference measurement between the arrival of an ion in the plastic scintillator and the measurement of a delayed γ ray via the DGF γ-time signal. The clock frequency of the DGF modules was 40 MHz, corresponding to a 25 ns time step. The maximum coincidence gate that could be achieved using the DGF modules was 400 μs.

The second output from the germanium preamplifier was sent to an analogue timing branch composed of a standard TFA-CFD-TDC timing circuit. The output of the CFD was sent to two separate TDC modules, one 'short-range' (1 μs full range with a 0.31 ns/channel step) and the other 'long range' (up to 800 μs with a 0.73 ns/channel step). The analogue branch allows a precise definition of shorter-lived ($\sim$ 10 ns) isomers.

2.3. Array performance: Efficiency and addback

The array performance was measured using radioactive sources both before and following the experimental beam time. The experimental conditions were found to produce an energy resolution of less than 3 keV at 1.3 MeV. The photopeak γ-ray efficiency was measured with several low intensity sources. To avoid dead time problems a pulser was used to emulate the plastic scintillator (which was used as the actual trigger during the experiments). Since the interval between the trigger pulses is longer than the acquisition dead time, the calibration is effectively dead time free. The efficiency is then, for each crystal, the number of γ rays observed divided by the number emitted during the live time of the acquisition. The former value is the number of triggers multiplied by the width of the time gates of the electronics.

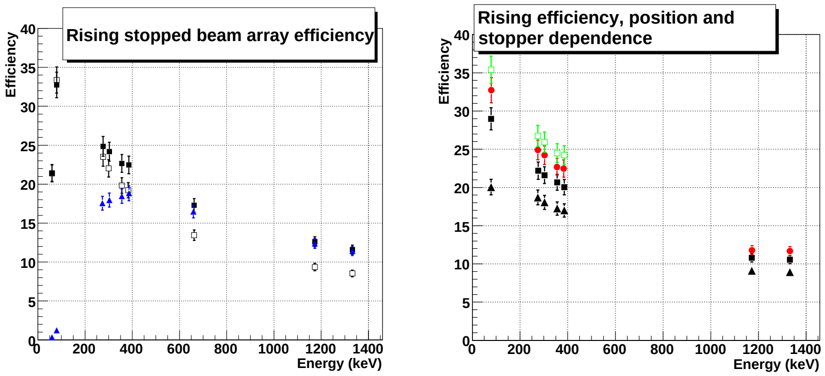

Fig. 3. Efficiency of the RISING array in its Stopped Beam configuration. Left: Comparison of sum (open squares), addback (full squares) and analog timing (triangles). Right: Efficiency for different stopper and positions. (Full circles) 7 mm perpex stopper, (empty squares) same stopper but source positioned 8 cm on the left, (full squares) 12 mm perpex stopper, (triangles) 6 mm copper stopper.

Fig. 3 shows an efficiency curve for a mixture of standard γ-ray sources placed in the middle of the Stopped Beam RISING array. During the experiments several stoppers were used depending the ultimate physics aim.

The attenuation of gamma rays following implantation in a given stopper depends on the stopper composition and on position and depth of the ion implantation. Fig. 3 shows the variation of the photopeak efficiency for several stoppers and as a function of the position of the γ-ray source. A GEANT4 simulation of the array is ongoing [17]. The preliminary results of this simulation reproduce our experimental data shown here. An "inter cluster" addback routine (*i.e.*, inclusion of Compton events scattered between crystals in *neighbouring* cluster detectors) is also being developed to increase further the absolute efficiency for low multiplicity events [18]. The full squares in Fig. 3 represent the efficiency with a Cluster Compton 'addback' routine allowing γ-ray multiplicities upto 4 per cluster such that the events are registered within 400 ns of each other. The triangle symbols represent the efficiency when requiring information in the timing (*i.e.*, TDC) branch of the acquisition. The difference in low energy efficiency arises due to the different discriminator types and settings, the leading edge type of the DGF having a sharper cutoff than the CFD of the analog timing branch. Note that the high efficiency below 100 keV arises from the absence of absorbers in front of the germanium cluster detectors.

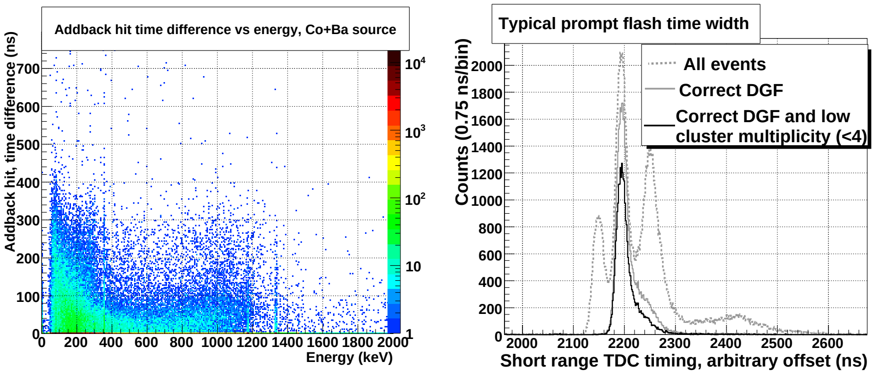

Fig. 4. Left: Time difference between hits in the addback *versus* summed γ-ray energy in the cluster detectors. Right: Time width of the prompt flash (see text for details).

Fig. 4 shows a two dimensional matrix of γ-ray summed energy versus time difference between γ-ray events used in that addback event. One can observe a significant increase in counts in that matrix for time difference less than 400 ns. The time width profile (*i.e.*, wider at lower energies) arises due to the fact that low energy γ rays typically interact in the outer most part of the crystal giving rise to the well known 'time walk' effect.

2.4. Experimental performance of the stopped beam array

Stopping ions with energies of several GeV in view of a high-efficiency γ-ray spectrometer such as RISING can be problematic due to the atomic radiation produced, the so-called 'prompt flash' [19]. This can cause multiple germanium detectors to fire with the prompt arrival of the ion and thus significantly reduces the effective efficiency for the measurement of delayed isomeric decays in the same event. This was a major concern in the previous fragmentation isomer campaign at GSI (see Ref. [8]) causing losses of up to 80% of the effective γ-ray efficiency. The high granularity of the 105 element RISING array is intended to overcome this problem. It was found that the flash multiplicity (*i.e.* number of crystal that fire during the ion implantation) depends on the energy of the implanted ion in the stopper [20]. A more systematic study, taking into account the stopper material and implantation position and depth is underway. Typical mean flash multiplicities range between 5 out of the total 105 individual detectors for the lighter ions (such as those in the ^{90}Rh setting) to 15 for the heavy nuclei (*e.g.*, ^{204}Pt). In the determination of the minimum isomeric lifetime that can be measured, the time width of this prompt flash component is of significance. Fig. 4 shows a typical prompt flash time profile. The dotted grey line is the time profile of the flash in the absence of any further software selection, while the full line represents events of multiplicity lower than 4 in any cluster and valid γ-ray energy in the DGF. The full grey line is with the proper energy in the DGF condition only. The width of the prompt flash is typically $\sim$ 30 ns. The triple peak structure apparent here has been observed in the RISING fast beam campaigns [21] and is believed to be caused by fast,light particles produced either in the stopper or in the final focal plane degrader.

The typical flight time in the FRS being a few 100 ns and the maximum gate achievable with the DGF being of 400 μs, the setup is highly sensitive to γ-ray decays from isomers with lifetimes in the range 100 ns $\rightarrow$ 1 ms. Decays with large internal conversion coefficients are hindered in their decays in flight since they are typically fully stripped of electronic electrons. In such cases, the width of the prompt flash can become a limiting factor for the observation of short-lived ($\sim$10 ns) isomers such as reported in reference [9].

3. Initial nuclear structure and reaction mechanism studies

Two RISING Stopped Beam experimental campaign have been performed to date. The first campaign begun with an experiment using a ^{107}Ag beam with the aim of producing nuclei on and around the $N = Z$ line [5]. Odd–odd $N = Z$ nucleus are of particular interest since they allow the mapping of the $T = 1$ and $T = 0$ components of the nucleon–nucleon interaction. The experiment showed evidence for isomeric decays in the $N = Z$ nuclei

$^{82}_{41}$Nb and $^{86}_{43}$Tc, the results of which are presented elsewhere in these proceedings [22, 23]. In the next experiment a ^{208}Pb 1 GeV$/A$ beam was used to produce nuclei along and 'west' of the $N = 126$ shell closure. The initial results from this study experiments are presented in [13] and [24,25]. Finally in the first phase of experiments, a beam of ^{58}Ni was used to produce $^{54}_{28}$Ni and $^{54}_{26}$Fe to study mirror symmetries in those two $T = 1$ mirror nuclei, the initial results of this work can be found in [26].

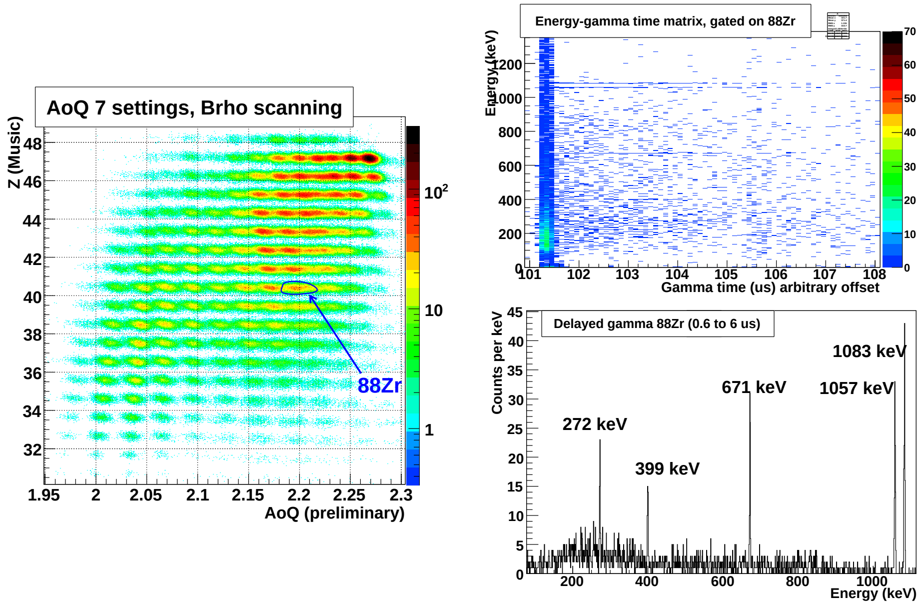

Fig. 5. Left: Sum identification plot for 6 of the 7 settings we made in Bρ scanning on the product of the ^{107}Ag 750 MeV$/u$ beam. Right: Energy time matrix gatted on $^{88}_{40}$Zr [32] from left, and energy spectra projected for a time range after the prompt flash (600 ns to 6 μs).

During July 2007 a second Stopped RISING experimental campaign took place with the same setup, with the specific aim of studying nuclei in and close the $N = 82$ shell closure. The exotic nuclei were produced using by through fragmentation of an ^{136}Xe beam and following the relativistic projectile fission of an ^{238}U beam. The data analysis for both of these experiments is currently in progress [27].

Part of the beam time was used to pursue nuclear reaction studies with the aim of using isomeric states as a probe to test how much spin is involved in a fragmentation reaction (as in reference [28]). Indeed, for a given isomer an estimate can be made of the isomeric ratio *i.e.*, the proportion of times a given nucleus populates this isomer compared to the total number of times the nucleus is created in the reaction. These type of studies are of particular interest for high-spin isomers such as those in ^{148}Tb or ^{147}Gd that were produced in the Stopped RISING experiment using the ^{208}Pb primary beam [25]. In such reaction studies having access of several types of observables in the same experiment allows a stringent test on the modelling of the physical reaction population and decay processes [29]. To this end, part of the ^{107}Ag primary beam time was used to perform Bρ scanning over a wide region of proton-rich nuclei in order to make measurements of nuclear production cross section and isomeric ratios (see Fig. 5). The modelling of the spin input in nuclear projectile fragmentation reactions follows the same formalism to that of the transfered linear momentum. Experimental access to the former is available through the position in the central focal point of the FRS. Thus it should be possible to make angular momentum population studies with respect to the transfered momentum for a wide range of final products using the ^{107}Ag. This analysis is currently in progress.

4. Summary and conclusions

Technical details of the RISING Stopped Beam setup have been presented together with an overview of the experiments carried out to date with this device. The setup will be upgraded with the addition of an active stopper which will allow the detection of the β decays from the implanted ions. This will allow β delayed γ-spectroscopy to be performed for heavy, exotic nuclei using a technique similar to that outlined in reference [30]. A proof of principle of this correlation can be found in [31].

This work is sponsored by the EPSRC (UK), the Swedish Research Council, the Polish Ministry of Science and Higher Education (grants 1-P03B-030-30 and 620/E-77/SPB/GSI/P-03/DWM105/2004-2007), the Spanish (Ministry of Education and Science (Minesterio de Education y Ciencias) under project number FPA2005-00696, the Bulgarian Science Fund VUF06/05, The US Department of Energy (grants DE-FG02-91ER-40609, W-31-109-ENG-38 and DE-AC02-06CH11357), the German Federal Ministry of Education and Research under grant 06KY205I and EURONS (European Commission contract number 506065). A.B.G. would also like to acknowledge financial support from the Nexia Solutions Ltd.

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