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Recent results in fragmentation isomer spectroscopy with rising

S. Pietri [a,*], P.H. Regan [a], Zs. Podolyák [a], D. Rudolph [b], S. Steer [a], A.B. Garnsworthy [a,c], E. Werner-Malento [d,e], R. Hoischen [b], M. Górska [d], J. Gerl [d], H.J. Wollersheim [d], I. Kojouharov [d], H. Schaffner [d], F. Becker [d], P. Bednarczyk [d,f], L. Caceres [d,g], P. Doornenbal [d], H. Geissel [d], J. Grębosz [d,f], A. Kelic [d], N. Kurz [d], F. Montes [d], W. Prokopowicz [d,h], T. Saito [d], S. Tashenov [d], A. Heinz [c], M. Pfützner [e], T. Kurtukian-Nieto [i], G. Benzoni [j], M. Hellström [b], A. Jungclaus [g], J. Simpson [k], L.-L. Andersson [b], L. Atanasova [l], D. Balabanski [l,m], M.A. Bentley [n], B. Blank [o], A. Blazhev [p], C. Brandau [a,d], J.R. Brown [n], A.M. Bruce [q], F. Camera [j], W.N. Catford [a], I.J. Cullen [a], Zs. Dombrádi [r], E. Estevez [i], C. Fahlander [b], W. Gelletly [a], G. Ilie [p], E.K. Johansson [b], J. Jolie [p], G.A. Jones [a], M. Kmiecik [f], F.G. Kondev [s], S. Lalkovski [l], Z. Liu [a], A. Maj [f], S. Myalski [f], T. Shizuma [a,t], A.J. Simons [a], S. Schwertel [u], P.M. Walker [a], O. Wieland [j]

[a] *Department of Physics, University of Surrey, Guildford GU2 7XH, UK*
[b] *Department of Physics, Lund University, S-22100, Lund, Sweden*
[c] *WNSL, Yale University, New Haven, CT 06520-8124, USA*
[d] *GSI, Planckstrasse 1, D-64291 Darmstadt, Germany*
[e] *IEP, Warsaw University, Hoża 69, PL-00-681, Poland*
[f] *The Henryk Niewodniczański Institute of Nuclear Physics, PL-31-342, Kraków, Poland*
[g] *Departamento de Fisica Teórica, Universidad Autonoma de Madrid, E-28049 Madrid, Spain*
[h] *Jagellonian University, PL-31-342 Kraków, Poland*
[i] *Universidad de Santiago de Compostela, E-15706 Santiago de Compostela, Spain*
[j] *INFN, Universitá degli Studi di Milano, I-20133 Milano, Italy*
[k] *CCLRC Daresbury Laboratory, Daresbury Warrington, Cheshire WA4 4AD, United Kingdom*
[l] *Faculty of Physics, University of Sofia, BG-1164, Bulgaria*
[m] *Dipartimento di Fisica, Universitá di Camerino, I-62032, Italy*
[n] *Department of Physics, University of York, Heslington, York Y01 5DD, UK*
[o] *CENBG, le Haut Vigneau, F-33175 Gradignan Cedex, France*
[p] *IKP, Universität zu Köln, D-50937 Köln, Germany*
[q] *School of Engineering, University of Brighton, Brighton BN2 4GJ, UK*
[r] *Institute for Nuclear Research, Debrecen H-4001, Hungary*
[s] *Nuclear Engineering Division, Argonne National Laboratory, Argonne IL-60439, USA*
[t] *Japan Atomic Energy Agency, Kyoto 619-0215, Japan*
[u] *Physik Department E12, Technische Universität München, Garching, Germany*

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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

* Corresponding author. Tel.: +44 1483 682730; fax: +44 1483 686781.
E-mail address: s.pietri@surrey.ac.uk (S. Pietri).

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structure physics research aimed at using relativistic energy (typically around 1 GeV per nucleon) projectile fragmentation reactions to populate nuclei with highly exotic proton-to-neutron ratios compared to the line of beta stability. In its high-efficiency 'stopped beam' configuration, the RISING γ-ray spectrometer consists of 105 individual, large volume germanium crystals which view a focal plane in which the exotic nuclei are brought to rest (i.e. 'stopped'). Here, decays from metastable or 'isomeric' 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 of initial commissioning experiments are also shown and details of the planned future experimental program are given.

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Keywords: γ-Ray spectroscopy; Nuclear isomers; Nuclear structure

1. Introduction

The aim of the RISING collaboration is to study exotic nuclei through beam fragmentation or projectile fission at energies provided by the SIS synchrotron at GSI of a few hundreds of MeV per nucleon. Previous experimental campaigns have used these detectors for studies of 'in-beam' γ-ray spectroscopy at relativistic energies [1]. RISING was moved to its stopped beam configuration for the first time in February 2006 (Fig. 1). Two subsequent experimental campaigns have now been performed aimed at the study of nuclear structure using the isomer-delayed γ-ray spectroscopy technique as outlined in [2–4]. Some brief technical details of a selection of these experiments and the performance characteristics of the RISING array in this configuration are presented below.

2. Technichal details

2.1. Basic isotope production, selection and identification

The production of exotic beams is done by the fragmentation of a stable beam from SIS on a thick (typically a few g/cm^2) ^{9}Be target. The two-stage FRagment Separator (FRS) [5,6] is used in achromatic mode for the selection and identification of the reaction products using time of flight (ToF) and energy loss measurements. Through position determination as measured with plastic scintillators at the first and second focal plane of the FRS, the magnetic rigidity of the individual ions can be accurately determined. The time of flight information provided by these fast plastic scintillators allows the determination of the particle velocity, from which a mass over charge (A/Q) ratio can be

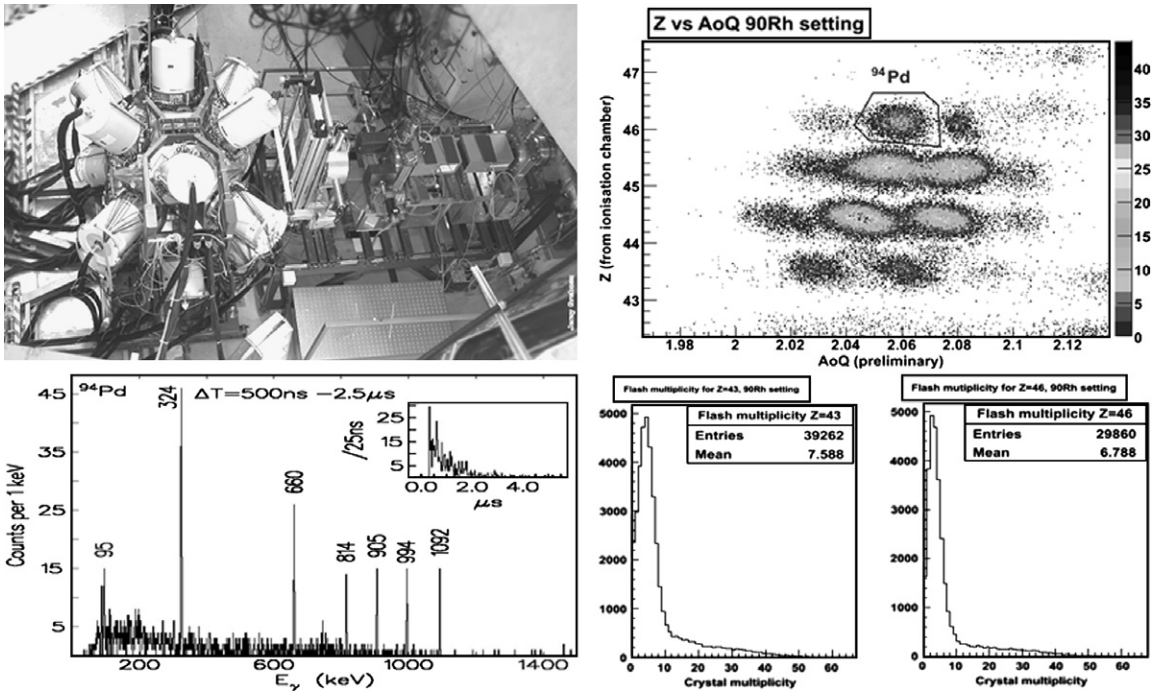

Fig. 1. Up left: the RISING stopped beam set-up, see text for details. Up right example of particle identification spectra obtained following the projectile fragmentation of the ^{107}Ag beam. The ^{94}Pd ions are selected and used to gate the delayed γ-ray energies observed between 500 ns and 2.5 μs following the ion implantation in the passive (perspex) stopper. These conditions produce the spectrum in the bottom left portion of the figure which shows gamma cascade associated with the $I^{\pi} = 14^{+}$ isomer in ^{94}Pd [2,9]. Bottom right: measured multiplicity of crystals which fired associated with the particle identification spectrum shown in Fig. 2-up for two different elements.

derived when the magnetic rigidity ($B\rho$) is known. Finally the charge is determined by two MUlti Sampling Ionization Chambers (MUSIC) at the end of the FRS (see Fig. 1) which measure the energy loss of the individual ions. A variable thickness aluminum degrader at the second focal point is used to slow down the ions such that they can be implanted in a passive stopper at the center of the germanium array. In the initial stopped RISING experiments, passive stoppers made from perspex, copper and beryllium were used. To minimize the transmission of hydrogen and higher charge states, niobium stripper foils were placed after the production target and the achromatic degrader.

2.2. The 'stopped beam' rising array

2.2.1. Technical data

The RISING array in its stopped beam configuration comprises 15 seven-element germanium cluster detectors [7] in a high-efficiency configuration (see Fig. 1). The detector were in three angular rings at 51°, 90° and 129° to the primary beam axis, each containing five cluster detectors. The average distance from the front face of the detectors to the centre of the passive stopped at the final focal place was approximately 22 cm. The measured photopeak γ-ray efficiency for the array in this geometry for sources placed in the center of the focal plane was approximately 15% at 661 keV.

2.2.2. Electronics

The two outputs from the Euroball pre-ampliers of the germanium detectors were sent to two separate electronics branch. The energy signal is processed by full digital electronic using DGF-4C modules from XIA [8]. This gives an energy resolution of less than 3 keV at 1.3 MeV under experimental conditions. Those modules have an internal clock with a 25 ns step which is used for the germanium timing signal. The fast plastic signal from the particle detector at the final focus of the FRS was also sent to each DGF crate to check the synchronization of the DGF crates. A second germanium preamplifier signal was sent to a conventional timing branch (TFA/CFD/TDC) with the TDC timing measured between the delayed gamma as a start signal and uses in 'common-stop' using the signal from the plastic in the second focal point. Two ranges of TDC were used, one with a short range of approximately 1.2 μs to give a good definition for short-lived (~10 ns) isomers and the CAEN 767 TDC with a range up to 800 μs. The total range for timing correlations between implanted ions and delayed γ-rays was determined by the maximum width of the DGF max coincidence window (400 μs).

3. Selected experimental results

During Feburary–March 2006 three experiments were performed using the stopped beam RISING set-up using beams of ^{58}Ni, ^{107}Ag and ^{208}Pb on Be production targets. The main physics aims of these studies were (i) the study of isospin symmetry $N = Z$ nuclei and (ii) the study of shell-model states in neutron-rich nuclei around the $N = 126$ shell gap. In addition, these experiments provided significant new information on the nuclear reaction mechanism associated with the population different angular momentum states in projectile fragmentation reactions.

Fig. 1 shows an example particle identification and delayed γ-ray spectra from the ^{107}Ag beam experiment using the DGF timing branch. The clean separation of the previously reported $I^{\pi} = 14^{+}$ isomer in ^{94}Pd [2,9] is readily apparent.

One of the major problems with previous fragmentation isomer studies has been a loss of γ-ray detection efficiency under the experimental conditions due to the so-called 'prompt flash' associated with light particles and bremsstrahlung during the slowing down process in the passive stopper which are observed by the germanium detectors [3]. One of the main drivers behind the design of the stopped beam array was its increased granularity over previously used set-ups [3,4]. Fig. 1 shows the measured prompt γ-ray multiplicity for Tc and Pd residues observed using the ^{107}Ag primary beam stopped in 7 mm of perspex in the center of the stopped RISING array. These results suggest that in this experiment only ~5% of the individual detectors were 'blinded' by this prompt radiation compared to values of ~80% in the closer geometry set-up [4]. The extra granularity of the RISING set-up thus clearly provides a major increase in the experimental efficiency for such studies.

3.1. Charge state separation and internal conversion suppression

In the majority of cases, the projectile fragmentation and fission products are transmitted through the FRS fully stripped of their atomic electrons (i.e. $Q = Z$), however, a fraction of the ions can be transmitted in other charge states, particularly hydrogen-like ions (i.e. $Q = Z - 1$). This can cause charge state anomalies and misidentification of ions unless accounted for. The technique outlined in [10] was used to discriminate between ions which do not change charge states between the first and second halves of the FRS (which are predominantly fully stripped ions) and those which pickup a electron (and thus change their charge by $-1e$) in the second portion of the FRS. This "$\Delta B\rho$, ΔE" technique [10] enhances the selection of fully stripped bare ions. Fig. 2 shows a particle identification plot for neutron-rich Pt and Au nuclei produced following the projectile fragmentation of a ^{208}Pb beam at 1 GeV per nucleon. The γ-ray spectra gated on fully stripped and hydrogen-like ^{204}Pt ($N = 126$ isotones of the beam) shown on the right side of Fig. 2 shows the effect the ionic charge state of the transmitted nuclei have on isomeric measurements. The transitions from isomeric decays in ^{204}Pt were observed for the first time in the February 2006 ^{208}Pb primary beam experiment. Two distinct isomers were

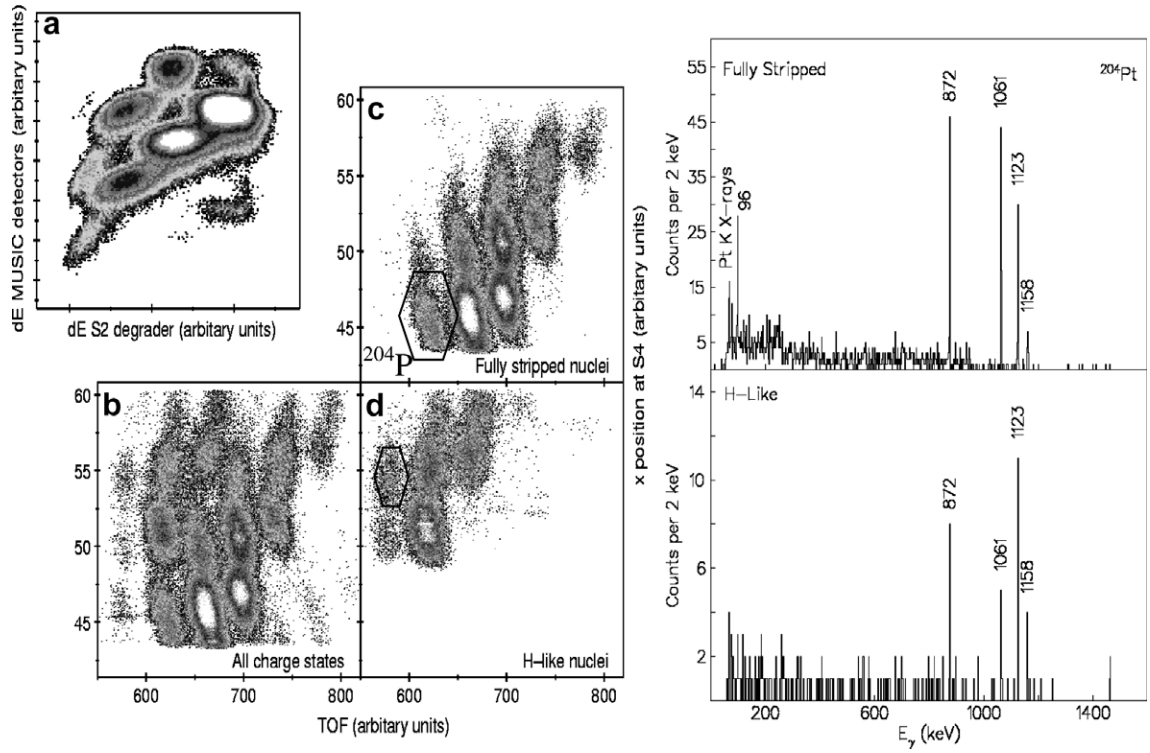

Fig. 2. (left) The charge state separation can be demonstrated using the deduced energy loss in the S2 degrader plotted against the energy loss of the ions in the MUSIC chambers. This can then be used to separate $Q = Z$ (fully stripped) and $Q = Z - 1$ (hydrogen-like) ions. (right) Transitions identified for the first time following isomeric decays in the $N = 126$ isotone ^{204}Pt for the first time following the fragmentation of a ^{208}Pb beam. The effect of fully stripping the ions of electrons and thus 'switching off' the internal conversion decay branches in flight is clearly demonstrated by the reduced observation of the 96, 1061 and 1158 keV transitions in the hydrogen-like spectrum (lower) compared to the fully stripped one (upper).

observed in this nucleus; with the higher-lying having a significant decay branch associated with a highly-converted, low-energy transition (96 keV). This internal conversion decay branch is 'switched off' for fully stripped ions and thus more of this decay survives through the few hundred nanosecond flight-time through the FRS. This is not the case for the same nucleus in the hydrogen-like state, where the decay can occur, thus explaining the difference between the relative intensities of the transitions shown in the upper and lower γ-ray spectra shown in Fig. 2.

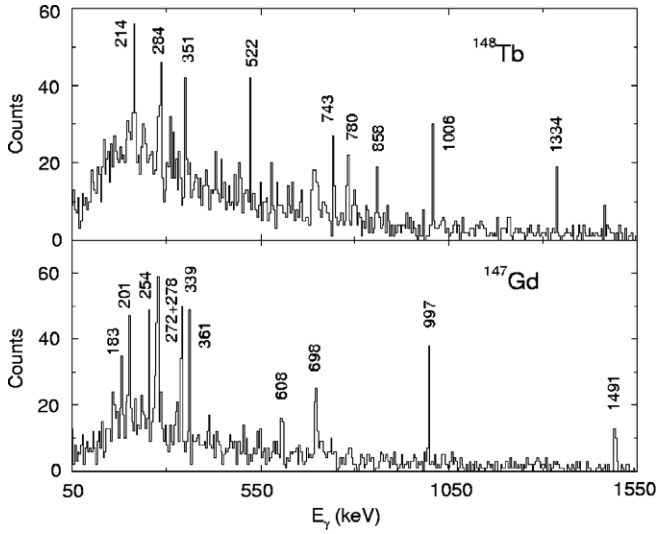

Fig. 3. γ-Ray spectra associated with the decays of the high-spin isomers in ^{147}Gd[11] and ^{148}Tb [12] as observed following the projectile of the ^{208}Pb beam. These decays represent the highest discrete spins observed to date in projectile fragmentation reactions.

3.2. High spin population in fragmentation

Fig. 3 shows the spectra associated with the previously reported isomers in ^{147}Gd [11] and ^{148}Tb [12] as observed in the current work following projectile fragmentation with the ^{208}Pb beam. The isomer in ^{148}Tb has an angular momentum of 27 h, which corresponds to the highest discrete angular momentum observed to date in projectile fragmentation reactions. The population and observation of such decay augurs well for future studies of high-spin states in exotic nuclei, particularly for neutron-rich species inaccessible with standard stable-beam/target fusion evaporation reactions.

4. Summary and conclusion

In addition to the brief results presented here from the ^{107}Ag and ^{208}Pb induced experiments, additional studies have now been performed using the stopped RISING set-up with ^{58}Ni, ^{136}Xe and ^{238}U primary beams. Highlights

from these studies include the identification of core breaking isomers in the ^{54}Fe/^{54}Ni mirror pair and the identification of 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 $A \sim 110$–130 nuclei and the implementation of a segmented silicon 'active stopper' placed in the centre of the RISING for β-delayed spectroscopy.

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