ISOMERIC RATIO FOR THE $I^\pi = 8^+$ YRAST STATE IN ^{96}Pd PRODUCED IN THE RELATIVISTIC FRAGMENTATION OF ^{107}Ag*

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

[a]H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences 31-342, Kraków, Poland
[b]Department of Physics, University of Surrey, Guildford, GU2 7XH, UK
[c]WNSL, Yale University, 272 Whitney Avenue, New Haven, CT, 06520, USA
[d]Department of Physics, Lund University, 22100, Lund, Sweden
[e]GSI, Planckstrasse 1, 64291, Darmstadt, Germany
[f]M. Smoluchowski Institute of Physics, Jagiellonian University 30-059 Kraków, Poland
[g]Universitá degli Studi di Milano and INFN sez. Milano, 20133 Milano, Italy
[h]CENBG, le Haut Vigneau, 33175, Gradignan Cedex, France
[i]School of Engineering, University of Brighton, Brighton, BN2 4GJ, UK
[j]Departamento de Fisica Teorica, Universidad Autonoma de Madrid, Spain
[k]Institute for Nuclear Research, 4001, Debrecen, Hungary
[l]Universidad de Santiago de Compostella, Santiago de Compostella, Spain
[m]IKP, Universität zu Köln, 50937, Köln, Germany
[n]National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[o]Nuclear Engineering Division, ANL, Argonne, IL 60439, USA
[p]Faculty of Physics, University of Sofia "St. Kliment Ohridsk" Sofia, Bulgaria
[r]Inst. of Experimental Physics, Warsaw University, Hoża 69, Warsaw, Poland
[s]Japan Atomic Energy Research Institute, Kyoto, 619-0215, Japan
[t]Physik Department E12, Technische Universität München, Garching, Germany

(Received November 11, 2006)

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

We report on the preliminary results from a study of the decay of the $I^\pi = 8^+$ $T_{\frac{1}{2}} = 2\mu$s isomer in ^{96}Pd performed as part of the Stopped-Beam RISING campaign within the Rare Isotope Investigation at GSI (RISING). The ^{96}Pd ions were produced following the projectile fragmentation of a 750 MeV per nucleon ^{107}Ag primary beam. The reaction products were separated and identified by the in-flight method using the GSI Fragment Separator. The residues of interest were stopped in a perspex stopper surrounded by an array of 15, seven-element germanium Cluster detectors. One of the goals of the current work is to investigate the population of high-spin states produced projectile fragmentation reactions using isomeric ratio measurements to infer information on the angular momentum population distribution. In this short contribution the method and results of determining the isomeric ratio for the $I^\pi = 8^+$ microsecond isomer in ^{96}Pd nucleus are presented.

PACS numbers: 23.20.Lv, 29.30.Kv

1. Introduction and experimental details

The production of exotic nuclei following projectile fragmentation reactions has opened up the possibility for isomer-delayed spectroscopy with beams at both intermediate (*e.g.*, [1–6]) and relativistic (*e.g.*, [7–12]) energies. One area of specific interest for future studies involves the angular momentum population in such reactions which can be investigated by measurements of the isomeric ratio of specific spin/parity states. Studies compared with the 'sharp cut off model' for heavy nuclei following the relativistic fragmentation of ^{208}Pb and ^{238}U beams [7, 11] have highlighted significant isomeric ratios associated with medium-to-high spin near-yrast states. In the current work, we investigate a similar population mechanism, but specifically for *proton*-rich nuclei. The determination of the final isomeric ratio requires corrections to account for effects such as the finite in-flight-separation time of the species of interest, relativistic time dilation, internal conversion, decay branching ratios, feeding from higher-lying isomeric states and γ-ray detection efficiency (see references [9, 11, 14] for details).

This short contribution focusses on the determination of the isomeric ratio for the proton-rich nucleus ^{96}Pd which decays by a cascade of four stretched E2 transitions from the $I^\pi = 8^+$ isomer [13].

The isomeric state in the exotic nucleus of interest was produced following projectile fragmentation reactions between a primary beam of ^{107}Ag and a 4 g/cm^2 thick ^{9}Be target. The ^{107}Ag primary beam energy was 750 MeV/u and was produced in 4 second wide time spills each containing about 1.6×10^7 ions. The different species were identified and separated through the FRS separator as described in Refs. [11, 14, 16]. At the final focus of the FRS was the RISING γ-ray array [14–16] which detects the γ-rays depopulating the states of interest. Further experimental details can be found in Refs. [14, 17, 18].

2. Data analysis and determination of the isomeric ratio

The analysis was performed with the CRACOW software [19]. From the experimental FRS observables, namely the time-of-flight (TOF) between the intermediate and final focal plane and energy loss at the final focal plane, a 2-dimensional particle identification histogram of A/Q *vs* Z can be created, enabling the selection of the nucleus of interest. Figure 1 shows the particle identification spectrum with the γ-ray energy and time spectra for the decay of the 8^+ isomer in the ^{96}Pd nucleus [13].

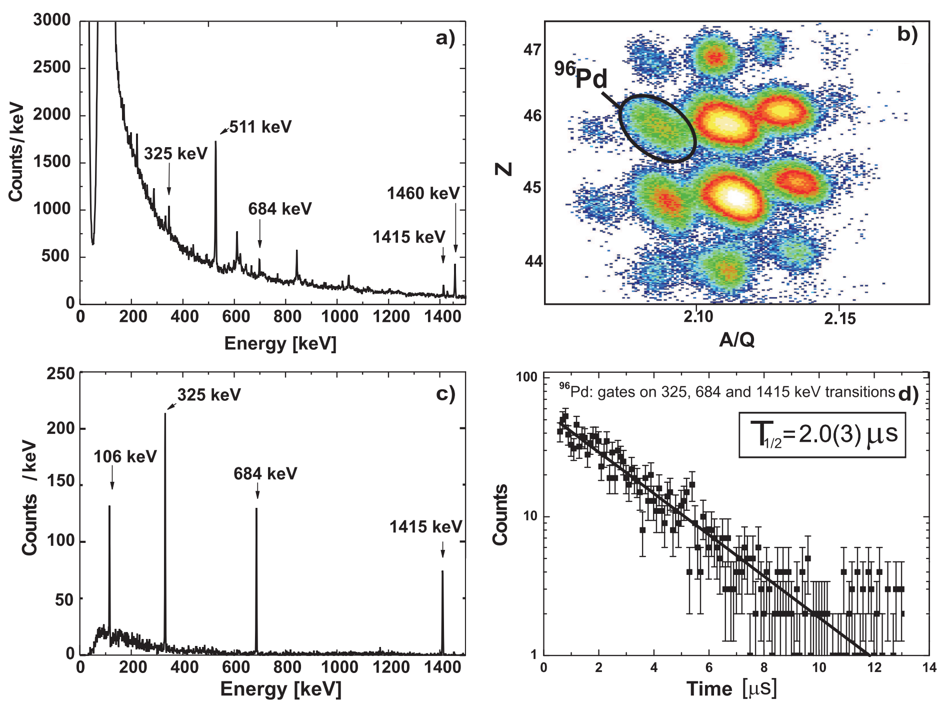

Fig. 1. (a) Ungated γ-ray spectrum; (b) Z *vs* A/Q particle-identfication spectrum showing region of fully-stripped ^{96}Pd ions; (c) ^{96}Pd ion-gated γ-ray spectrum between 150 ns and 14.7 μs following implantation in the perspex stopper; (d) Time decay spectra associated with the ^{96}Pd ions gated on the γ-ray transitions at 325, 684 and 1415 keV.

The isomeric ratio (R) is defined as the probability that in a reaction a given nucleus is produced in an given isomeric state [11]:

$$R = \frac{Y}{N_{\mathrm{imp}} F G}\,, \tag{1}$$

where N_{imp} is number of implanted heavy ions, Y is the yield, F is a correction factor for isomer losses and G is correction for finite detection time. N_{imp} is measured directly from the number of ions which are detected at the final focus of the FRS. On the other hand the yield, (Y) needs to be calculated from the intensity of γ-rays associated with the isomeric decay and corrected for in-flight losses, detection efficiency *etc.* In general, for ions which do not change charge state in flight,

$$Y = \frac{N_\gamma (1+\alpha)}{\varepsilon_{\mathrm{eff}} b_\gamma}\,, \tag{2}$$

where N_γ is intensity of gamma line at the specific energy, $\varepsilon_{\mathrm{eff}}$ is detector efficiency for that energy, α is internal conversion coefficient, and b_γ is the branching ratio. In the case of ^{96}Pd the decay follows only one branch (the 105, 325, 684 and 1415 keV transitions are all in a mutually coincident, 100% fed cascade [13]). If the ion is fully stripped of atomic electrons and the isomeric decay has a significant electron conversion branch, the decay can be significantly hindered and the effective 'in-flight' lifetime increased (*e.g.* [12]). Therefore we need also to calculate the factor F (in-flight correction for isomer losses) defined as

$$F = \exp\left[-\left(\lambda^{q_1}\frac{\mathrm{TOF}_1}{\gamma_1} + \lambda^{q_2}\frac{\mathrm{TOF}_2}{\gamma_2}\right)\right]\,, \tag{3}$$

where TOF_1 is flight time through the first part of separator, TOF_2 is flight time through the second part of separator, and accordingly γ_1 is the Lorentz factor in the first part and γ_2 corresponds to the second part. λ^{q_1} and λ^{q_2} are decay constants for the charge states in the first and the second half of separator. In the current work the ion is fully stripped during whole flight so $\lambda^{q_1} = \lambda^{q_2} = \lambda^0 = \lambda/(1+\alpha)$, with α being the conversion coefficient for the transition directly depopulating the isomer. For the first part, the flight time was estimated using the ion-optical code MOCADI [20] to be 149 ns. The second part can be measured directly comparing the timing signals from the two scintillators at the intermediate and final focal plane and was determined to be 177 ns. An internal conversion coefficient of $\alpha(\mathrm{E2}) = 1.13$ was used in the analysis for the 105 keV transition which directly depopulates the 8^+ isomer in ^{96}Pd.

Another important factor is the correction for finite detection time, (G) defined as

$$G = \exp(-\lambda t_{\rm start}) - \exp(-\lambda t_{\rm stop})\,, \tag{4}$$

where $t_{\rm start}$ is time of beginning of detection range, and $t_{\rm stop}$ is time of its end. For the spectra shown in Fig. 1, the delayed γ-ray detection range in the long-range TDCs [14] was from 150 ns to 14.7 μs following the ion implantation in the passive stopper.

To calculate the isomeric ratio, values of the half-life of the isomeric state must be known, which we measured in the current work to be 2.0(3) μs (see Fig. 1(d)). This half-life values was obtained by taking the sum of delayed γ-ray time projections in the long-range TDCs for the three strong lines at 325, 684 and 1415 keV associated with the decay cascade of the $I^\pi = 8^+$ isomer in ^{96}Pd [13]. The half-life deduced in the current work is consistent with the literature values for this isomer of 2.2(3) μs [13] and 1.7(1) μs [4]. Note also that the effective in-flight half-life for the fully-stripped ^{96}Pd ion in this experiment was calculated to be 4.3(6) μs due to the lack of any internal conversion decay branch in-flight.

We took into account the loss during the slowing down-implantation process due to nuclear reaction in the variable degrader mounted before stopper foil, which in this case corresponds to 10% of the nuclei.

Making these corrections and using the measured efficiency of the RISING array as discussed in reference [14], the value for the isomeric ratio of the yrast 8^+ state in ^{96}Pd was calculated.

Table I shows the calculated isomeric ratio values obtained using the 105 325, 684 and 1415 keV lines in the current analysis. Taking the weighted mean of these results, we obtain a value for the isomeric ratio of the $I^\pi = 8^+$ isomer in ^{96}Pd of $R = 20.5(10)$%.

TABLE I

Data for transitions used in analysis.
The number of implanted ^{96}Pd ions was $N_{\rm imp} = 1.63{\rm x}10^4$.

Energy [keV]	Counts	$\varepsilon_{\rm eff}$	α	R [%]
105	276	0.17(6)	$1.3{\rm x}10^{0}$	23.4(40)
325	549	0.19(2)	$2.26{\rm x}10^{-2}$	20.0(20)
684	351	0.13(1)	$2.54{\rm x}10^{-3}$	18.6(15)
1415	250	0.08(1)	$4.82{\rm x}10^{-4}$	20.1(15)

This value of isomeric ratio is of similar scale to the one obtained in Ref. [3], 39(6)%, although we note the two experiments were carried out in very different primary energy regimes and with different primary beams.

This work is sponsored by 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 Bulgarian Science Fund VUF06/05, the US Department of Energy (grants DE-AC02-06CH11357 and DE-FG02-91ER40609), the German Federal Ministry of Education and Research under grant 06KY205I and EURONS (European Commission contract number 506065), the Spanish Ministry of Education and Science (project FPA2005-00696).

REFERENCES

[1] C. Chandler *et al.*, *Phys. Rev.* **C61**, 044309 (2000).

[2] P.H. Regan *et al.*, *Acta Phys. Pol. B* **28**, 431 (1997).

[3] R. Grzywacz *et al.*, *Phys. Lett.* **B355**, 439 (1995).

[4] R. Grzywacz *et al.*, *Phys. Rev.* **C55**, 1126 (1997).

[5] R. Grzywacz *et al.*, *Phys. Rev. Lett.* **81**, 766 (1998).

[6] J.M. Daugas *et al.*, *Phys. Lett.* **B476**, 213 (2000).

[7] Zs. Podolyák *et al.*, *Phys. Lett.* **B632**, 203 (2006).

[8] Zs. Podolyák *et al.*, *Phys. Lett.* **B491**, 225 (2000).

[9] K.A. Gladnishki *et al.*, *Phys. Rev.* **C69**, 024617 (2004).

[10] M. Pfützner *et al.*, *Phys. Lett.* **B444**, 32 (1998).

[11] M. Pfützner *et al.*, *Phys. Rev.* **65**, 064604 (2002).

[12] M. Caamano *et al.*, *Eur. Phys. J.* **A23**, 201 (2005).

[13] H. Grawe, H. Haas, *Phys. Lett.* **B120**, 63 (1983); W.F. Piel Jr *et al.*, *Phys. Rev.* **C28**, 209 (1983).

[14] S. Pietri *et al.*, *Acta Phys. Pol. B* **38**, 1255 (2007), these proceedings.

[15] P.H. Regan *et al.*, Proceedings of the IXth International Conference on Nucleus–Nucleus Collisions, Rio De Janeiro, 2006, *Nucl. Phys.* **A**, in press.

[16] S. Pietri *et al.*, Proceedings of the 19$^{\rm th}$ International Conference on the Application of Accelerators in Research and Industry, CAARI'06, Fort Worth, USA, 2006, *Nucl. Instrum. Methods* **B**, in press.

[17] A. Garnsworthy *et al.*, *Acta Phys. Pol. B* **38**, 1265 (2007), these proceedings.

[18] L. Cáceres-Monllor *et al.*, *Acta Phys. Pol. B* **38** (2007), these proceedings.

[19] J. Grębosz, *Comput. Phys. Commun.* (2006), in press, doi:10.1016/j.cpc.2006.09.006.

[20] N. Iwasa *et al.*, *Nucl. Instrum. Methods Phys. Res.* **B126**, 284 (1997).