The isomeric structure of $^{132}$Pr

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Abstract. The isomeric structure of the neutron deficient nucleus $^{132}$Pr, located in the rare-earth region of the nuclear chart, has been studied with the $^{98}$Mo($^{40}$Ar,5pn)$^{132}$Pr reaction at beam energies of 150, 158 and 165 MeV. The experiment was performed at the University of Jyväskylä, Finland where the $^{40}$Ar beam was accelerated onto the target by the K130 cyclotron. The JUROGAM II HPGe detector array was employed in conjunction with the RITU gas-filled recoil separator. The focal-plane chamber housed a multi wire proportional counter and a position-sensitive silicon strip detector used for the implantation and identification of recoiling nuclei. The recoil-isomer tagging technique was used to correlate the delayed decays, measured in the Planar and Clover detectors of the GREAT spectrometer, with the known prompt transitions in $^{132}$Pr. Two new delayed transitions have been observed at energies of 102 and 118 keV. The corresponding X ray peaks are consistent with Pr $K\alpha$ and $K\beta$ X rays with energies of 35.63 and 40.91 keV, respectively. The half-life of the newly established isomeric state, from which the 102 and 118-keV transitions proceed, has been measured to be 2.5(3) $\mu$s.

1. Introduction

Several experiments which have recently taken place at the University of Jyväskylä concentrated on the study of isomeric states in the neutron deficient $N = 73$ and $N = 75$ isotones [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. The nuclei measured in these studies were observed to exhibit properties associated with deformed shapes [11]. In the $A \approx 130$ region, the competing shape-driving effects of protons occupying lower-$\Omega$, prolate driving $h_{11/2}$ orbitals and neutrons in the higher-$\Omega$, oblate-driving $h_{11/2}$ orbitals can create the possibility for the existence of shape isomers. By measuring the half-life of these isomeric states, as well as the properties of the transitions that directly feed the isomers, it is possible to determine their structures. The aim of the present experiment was to discover new transitions below a tentatively established $(7^{-})$ state in $^{133}$Pr, whose excitation energy and lifetime was previously unknown, and connect the proposed high and low-spin parts of $^{132}$Pr level scheme together [12, 13, 14]

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2. Experimental methods
In order to study $^{132}$Pr an experiment was performed at the University of Jyväskylä, Finland in August 2010. The heavy-ion fusion-evaporation reaction $^{98}$Mo($^{40}$Ar,5pn), at beam energies of 165, 158 and 150 MeV, was used to populate excited states in $^{132}$Pr [14, 15]. The K130 cyclotron accelerator was used to accelerate a beam of $^{40}$Ar nuclei onto a fixed target, and the subsequent $\gamma$ rays produced from the de-excitation of the $^{132}$Pr nuclei were measured by the JUROGAM II array at the target position. After transmission through the Recoil Ion Transport Unit (RITU), a gas-filled recoil separator, the nuclei were implanted into two Double-Sided Silicon Strip Detectors (DSSDs) and any further $\gamma$-ray decays were observed using the Planar and Clover detectors of the GREAT spectrometer. Recoil-isomer tagging was used to correlate prompt transitions, measured at the target position, with delayed decays at the focal plane. Events were time stamped by a 100-MHz clock through the triggerless total data readout (TDR) acquisition system [16]. Data were collected for off-line sorting with the GRAIN software package [17], and sorted into two-dimensional spectra (matrices) for analysis with the UPAK software suite [18].

3. Results
The analysis of data collected in the Planar and Clover detectors of GREAT revealed that the most intense delayed transitions were those populated via $\beta$ decay. Short-lived isomeric transitions were isolated from the $\beta$ delayed transitions in the focal-plane spectra by imposing a recoil delayed-$\gamma$ time constraint of 0-9 $\mu$s and subtracting a long-lived background of 20-29 $\mu$s. All spectra, except those used to measure decay half lives, were produced with this recoil delayed-$\gamma$ time constraint. The present work has managed to successfully isolate two new delayed transitions, which have been associated with prompt decays in $^{132}$Pr, and examine several of their properties.

3.1. Prompt-delayed $\gamma$-$\gamma$ analysis
A peak at 176 keV was observed in the Planar Ge spectrum which was identified and confirmed as being the decay from the proposed (9/2)- isomer in $^{133}$Nd [19]. A prompt-delayed coincidence matrix was produced and the delayed projection highlighted two unidentified peaks at 101.5(9) and 117.7(9) keV. Figure 1(a) shows a sum gate on the delayed 102 and 118-keV $\gamma$ rays. All labeled peaks were identified as prompt transitions in $^{132}$Pr [14]. Figure 1(b) shows the two delayed $\gamma$-ray transitions, 102 and 118-keV, from a sum of gates on the prompt 115-, 130-, 178-, 265- and 283-keV transitions in $^{132}$Pr. The 36- and 41-keV peaks are the $K_\alpha$ and $K_\beta$ X rays of Pr, respectively which are consistent with theoretical calculations of the Pr $K_\alpha$ and $K_\beta$ X rays with energies of 35.63 and 40.91 keV, respectively.

The low X-ray intensities in Figure 1(b) are due to the low Planar Ge efficiency for this set-up, measured as $\sim$ 9 % and $\sim$22% , relative to that at 100 keV, for $\gamma$ decays at 36 and 41 keV, respectively.

3.2. Delayed-delayed $\gamma$-$\gamma$ analysis
Figure 2 shows a Planar Ge spectrum created by gating on the 118-keV transition, Fig. 2(a) and the 102-keV transition, Fig. 2(b) recorded in the focal plane Clover detector. Inspection of the $^{132}$Pr low-energy decay scheme [15] shows two parallel transitions with energies 102.4(3) and 117.9(2) keV. It is clear from Fig. 2(a) and (b) that the observed delayed transitions in this work are in coincidence and therefore cannot be the transitions reported in Ref. [15].
Figure 1. Recoil-isomer-tagged spectra from a prompt-delayed matrix where the delayed $\gamma$ rays were detected 0-9 $\mu$s after a recoil implanted into the DSSD. A background time subtraction was performed for the interval 20-29 $\mu$s. (a) Prompt JUROGAM II spectrum showing the established transitions in $^{132}$Pr [14] along with the newly observed 184 and 308-keV prompt transitions in from a sum of gates on the delayed 102 and 118-keV $\gamma$ rays. All labeled peaks have been previously assigned to $^{132}$Pr. (b) Delayed planar spectrum showing the 102 and 118-keV delayed transitions from a sum of gates on the prompt 115-, 130-, 178-, 265- and 283-keV transitions in $^{132}$Pr. The inset spectrum shows the low-energy X-ray region expanded for clarity.

3.3. Electron-conversion coefficient
The nature of the 102 and 118-keV transitions depopulating the newly established isomeric state in $^{132}$Pr were deduced by consideration of their electron-conversion coefficient. The experimental K-shell electron-conversion coefficient for the transitions at 102 and 118 keV are $\alpha_k = 2.65 \pm 0.17$ and $0.6 \pm 0.05$, respectively. In comparison, the calculated K-shell conversion coefficients for a 102 and 118 keV transition in $^{132}$Pr are $\alpha_k(E1) = 0.207(3)$, $0.1356(19)$, $\alpha_k(M1) = 1.072(15)$, $0.689(10)$ and $\alpha_k(E2) = 1.177(17)$, $0.741(11)$, respectively. The experimental K-shell electron -conversion coefficients associated with the 102 and 118 keV $\gamma$-ray transitions indicate either E2 or M1 [20].

3.4. Half-life analysis
The half-life of 176-keV delayed transition, which is already established in $^{133}$Nd [21], was measured to be $t_{1/2} = 303 \pm 2.4$ ns. This is in agreement with previous measurements and was used as a calibration for the measurement of new transitions. The half-life of the new isomeric state in $^{132}$Pr was determined from a focal-plane time spectrum gated on the delayed 102 and 118 -keV $\gamma$-ray transitions. The time parameter in these spectra was defined as the time difference between a recoil passing through the MWPC and a $\gamma$-ray detected in the Planar Ge detector using the 100 MHz TDR clock. In this work, the half-life of the isomeric state in $^{132}$Pr was deduced to be $2.5(3)$ $\mu$s. Figure 3(a) and (b) show the half-life for the 176 and 102-keV transitions in $^{133}$Nd and $^{132}$Pr, respectively.
Figure 2. (a) Planar spectrum highlighting the 102-keV transition after gating on the delayed 118-keV $\gamma$-ray in the Clover detector. (b) Planar spectrum highlighting the 118-keV transition after gating on the delayed 102-keV $\gamma$-ray in the Clover detector.

Figure 3. (Color online) (a) Time spectrum for 176-keV delayed $\gamma$-ray transition in $^{133}$Nd. (b) Time spectrum for the new 102-keV delayed $\gamma$-ray transition in $^{132}$Pr. The ”Time” axis label refers to the time difference between a recoil passing through the MWPC and the detection of the delayed $\gamma$ ray in the Planar or Clover detector.
4. Conclusion and outlook
The recoil-isomer tagging technique, performed at the university of Jyväskylä was used to correlate delayed decays with the known prompt transitions in $^{132}$Pr, built upon a tentatively established state of unknown excitation energy. A new isomer has been established. Two new delayed transitions have been observed at energies of 102 and 118 keV. Prompt transitions previously established in $^{132}$Pr have been measured in coincidence with the newly identified delayed transitions. The half-life of the isomeric state in $^{132}$Pr was determined from a series of focal plane time spectra gated on the delayed 102 and 118 keV $\gamma$-ray transitions. The half-life of the isomeric state has been measured to be $2.5(3)$ $\mu$s. This work is still in progress and these findings are preliminary.

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