ISOMER SPECTROSCOPY OF NEUTRON-RICH ^{165,167}Tb*

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We present information on the excited states in the prolate-deformed, neutron-rich nuclei $^{165,167}Tb_{100,102}$. The nuclei of interest were synthesised following in-flight fission of a 345 MeV per nucleon ^{238}U primary beam on a 2 mm ^{9}Be target at the Radioactive Ion-Beam Factory (RIBF), RIKEN, Japan. The exotic nuclei were separated and identified event-by-event using the BigRIPS separator, with discrete energy gamma-ray decays from isomeric states with half-lives in the μs regime measured using the EURICA gamma-ray spectrometer. Metastable-state decays are identified in ^{165}Tb and ^{167}Tb and interpreted as arising from hindered E1 decay from the $\frac{7}{2}^{-}[523]$ single quasi-proton Nilsson configuration to rotational states built on the $\frac{3}{2}^{-}[411]$ single quasi-proton ground state. These data correspond to the first spectroscopic information in the heaviest, odd-A terbium isotopes reported to date and provide information on proton Nilsson configurations which reside close to the Fermi surface as the ^{170}Dy doubly-midshell nucleus is approached.

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1. Introduction

The single-particle structure of states in quadrupole-deformed nuclei in the vicinity of the ^{170}Dy valence maximum nucleus can be used as a measure of the magnitude of the (prolate) deformation in these systems [1, 2]. The terbium isotopes ($Z = 65$) correspond to a single proton–hole in the ^{170}Dy deformed core [3] and, therefore, their structure can be used to probe the evolution of competing, prolate-deformed single-particle structures in this region of the Segré chart. Prior to this work, ^{163}Tb was the heaviest isotope of this element for which excited state information had been reported [4] and the systematics of the lighter odd-A Tb isotopes $^{161,163}Tb$ are consistent with ground states built on the same $\frac{3}{2}^{+}[411]$ Nilsson single quasi-proton configuration [1, 2, 4, 5]. Here, we report on the decay of isomeric states in the neutron-rich systems ^{165}Tb and ^{167}Tb, and compare the deduced level schemes with long-standing predictions of which quasi-proton orbitals are favoured in this well-deformed region of the nuclear chart.

2. Experimental details and results

The nuclei of interest were created following production via the projectile fission mechanism at the Radioactive Isotope Beam Factory (RIBF) [6], RIKEN, Japan. The production synthesis used collisions between a ^{238}U primary beam of the energy of 350 MeV/u on a 2 mm thick Be target with a typical on-target beam current of 10 pnA. The secondary cocktail beam of in-flight fission fragments was separated using the BigRIPS Separator and the ZeroDegree spectrometer [7, 8] at RIBF. Specific radionuclide species could be tagged on an event-by-event basis using measured parameters of magnetic rigidity ($B\rho$), Time-of-Flight (ToF) and energy loss (ΔE) for the ions as they passed through the separator [9, 10]. The primary fission residues were subsequently stopped in the Wide-range Active Silicon Strip Stopper Array (WAS3ABI) [11] which allowed direct detection of the implanted heavy ion and also subsequent position correlated β-decay events from the same ion. The WAS3ABI stopper was surrounded by the Euroball RIKEN Cluster Array (EURICA) which allowed the detection of the delayed gamma rays emitted following the decay of heavy-ion correlated isomeric or beta-delayed events. In this experiment, EURICA consisted of 84 coaxial High-Purity Germanium (HPGe) detectors, arranged in an array of 12×7 element CLUSTER detector modules, complemented by 18 $LaBr_3$(Ce) detectors for fast-timing measurements [12–14].

The current work reports on data from two distinct magnetic rigidity ($B\rho$) settings: one centred on the transmission of ^{170}Dy ions, which ran for 13.5 hours [3]; and a second one centred on the transmission of ^{172}Dy [15] for 45 hours. The particle-identification (PID) plots for both settings are shown in figure 1. These PID plots show ions which are transmitted both as fully-stripped ($Q = Z$) and also as hydrogen-like ($Q = Z - 1$) species. By gating on defined isotopes, gamma-ray energies measured in the EURICA spectrometer were correlated, event-by-event with isomeric decays. Figure 2 shows the EURICA gamma-ray spectra gated on isomer-delayed decays from ^{165}Tb and ^{167}Tb in the current work.

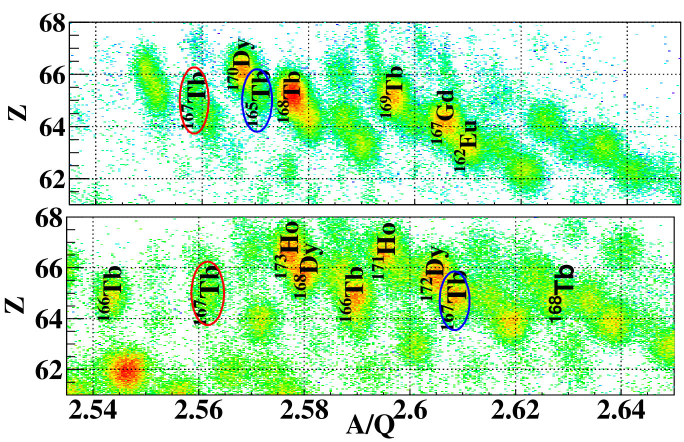

Fig. 1. (Colour on-line) Particle identification plots obtained from the two BigRIPS settings used in this work. (Upper) PID for the first setting centred on ^{170}Dy, identifying the H-like ^{165}Tb and fully-stripped ^{167}Tb ions: (Lower) PID for the second setting centred on ^{172}Dy, identifying fully-stripped (grey/red circle) and H-like (black/blue circle) ^{167}Tb events.

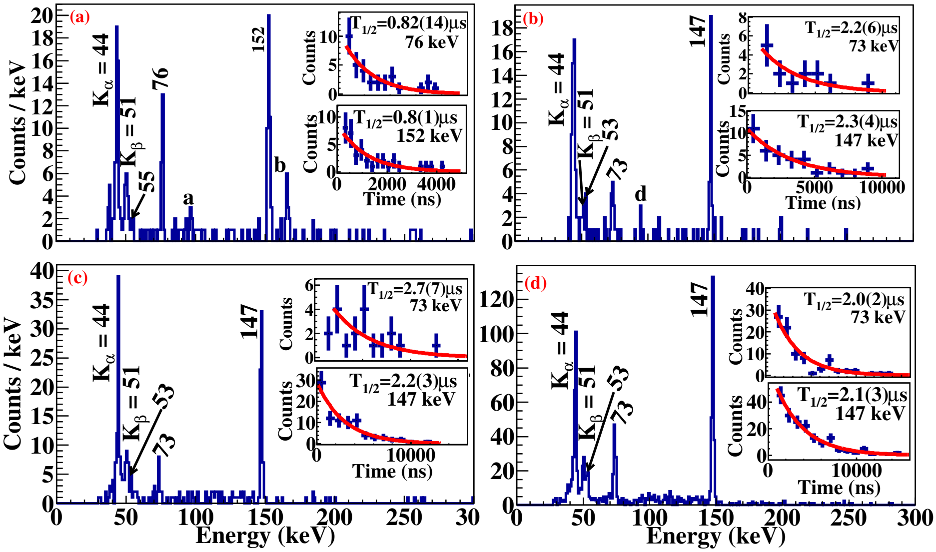

Fig. 2. Ion-gated, delayed HPGe gamma-ray spectra for EURICA showing transitions associated with the isomeric decays in (a) H-like ^{165}Tb and (b) fully-stripped ^{167}Tb from the ^{170}Dy centred setting; and (c) fully-stripped and (d) H-like ^{167}Tb ions in the ^{172}Dy centred setting. The gamma-ray coincidence time condition used to generate these spectra were 400 ns to 2 μs after the ^{165}Tb implantation in WAS3ABI and 200 ns to 5 μs for ^{167}Tb. The insets in each spectrum show the projected time distribution after of the measured gamma-ray transitions following implanation, fitted to a single-component exponential decay.

The spectrum shown in figure 2 (a) identifies gamma rays following the isomeric decay in ^{165}Tb. Discrete energy peaks are evident at 76 and 152 keV and a smaller peak is noted at 55 keV; this latter peak can be resolved from the observed characteristic terbium K X-ray peaks at 44 and 51 keV. Contaminant peaks, labelled “a” and “b”, are also noted in this spectrum from overlaps with misidentified ^{168}Tb [16] and ^{170}Dy [3] ions. The time distributions for the 76 keV and 152 keV transitions yields fitted values of 0.82(14) μs and 0.8(1) μs, implying that both of these transition energies are associated with the decay of a single isomeric state. The weighted mean of these two measurements gives a half-life value for the isomeric state in ^{165}Tb of $T_{1/2} = 0.81(8)$ μs.

The delayed gamma-ray spectra associated with fully stripped and H-like ^{167}Tb ions are also shown in figure 2. Discrete energy peaks at 53, 73 and 147 keV are evident, together with the expected K X-rays from terbium, which are assumed to arise from the competing conversion electron decay process. The time distributions for the measurement of the 73 and 147 keV lines relative to the implantation time are shown for the three different ^{167}Tb identification positions, with a weighted mean of these six independent half-life distributions of $T_{1/2} = 2.1(1)$ μs.

Figure 3 shows the gamma-ray coincidence spectra associated with gates on transitions identified in the isomeric decay of ^{165}Tb and ^{167}Tb. Gamma-ray coincidences between these identified transitions were investigated for ^{167}Tb. These show that the 73 keV transition is a self-coincident doublet with additional coincidences with the Tb K X-rays. This suggests that one of the members of the 73 keV doublet has a relatively large internal electron conversion coefficient and perhaps that the two members of the doublet have different multipolarities. The coincidence data and energy sum considerations imply that the 147 keV decay transition provides a parallel decay path from the isomeric state in ^{167}Tb which competes with a cascade of two, mutually coincident transitions of energy 73 keV. Both of these competing decay paths appear to populate the first excited state at the energy of 53 keV. The internal conversion coefficients and intensity balances (see Table I) for the proposed level scheme imply an E1 multipolarity for the 147 keV transiton (α(E1:147 keV) = 0.1067) and an M1 decay for the 53 keV transition (α(M1:53 keV) = 13.5). The 73 keV doublet is interpreted as being an E1 transition (α(E1:73 keV) = 0.694) followed by a predominantly M1 in-cascade decay (α(M1: 73 keV) = 5.44). For ^{165}Tb, the statistics are poor, but essentially the same behaviour is evident, in this case, two 76 keV transitions in parallel with a 152 keV transition. The tentative level schemes associated with the isomeric decays in ^{165}Tb and ^{167}Tb as proposed in the current work are shown in figure 4.

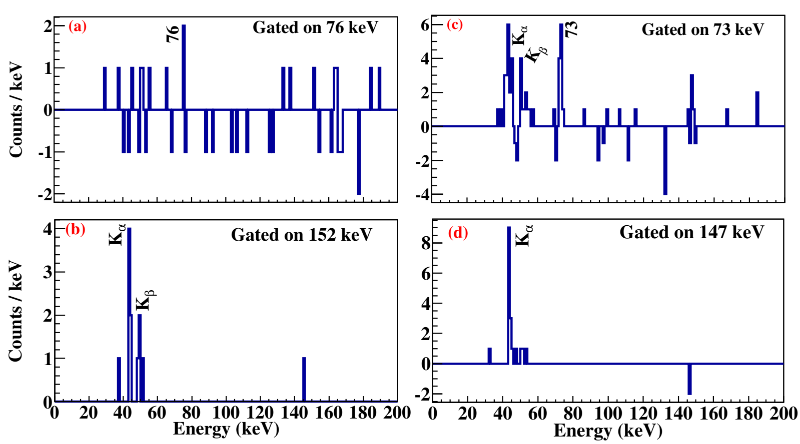

Fig. 3. Left: Gamma-ray coincidence spectra gated on the (a) 76 keV and (b) 152 keV transitions associated with the isomeric decay of ^{165}Tb. Right: Gamma-ray coincidence spectra gated on the (c) 73 keV and (d) 147 keV transitions associated with the isomeric decay of ^{167}Tb observed in the current work.

TABLE I

Single quasi-particle isomers in ^{165,167}Tb decaying via E1 and M1 transitions for first setting.

Nucleus	E_γ [keV]	I_i^π	I_{rel}	α_{tot}	$I_{rel}(\alpha_{tot}+1)$
^{165}Tb$^{(H)}$	$152(2)^{E1}$	$\left(\frac{7}{2}^-\right)$	1.9(3)	0.0975(14)	2.12(27)
	$76(2)^{E1}$	$\left(\frac{7}{2}^+\right)$	0.72(10)	0.624(9)	1.17(16)
	$76(2)^{M1}$	$\left(\frac{5}{2}^+\right)$	0.20(3)	4.84(7)	1.17(18)
	$55(4)^{M1}$	$\left(\frac{3}{2}^+\right)$	0.21(3)	12.28(18)	2.78(44)
^{167}Tb$^{(F)}$	$147(4)^{E1}$	$\left(\frac{7}{2}^-\right)$	1.2(2)	0.1067(15)	1.33(18)
	$73(4)^{E1}$	$\left(\frac{7}{2}^+\right)$	0.48(6)	0.694(10)	0.81(11)
	$73(4)^{M1}$	$\left(\frac{5}{2}^+\right)$	0.13(2)	5.44(8)	0.83(18)
	$53(4)^{M1}$	$\left(\frac{3}{2}^+\right)$	0.21(4)	13.51(19)	3.05(59)

H → Hydrogen-Like; F → Fully-Stripped

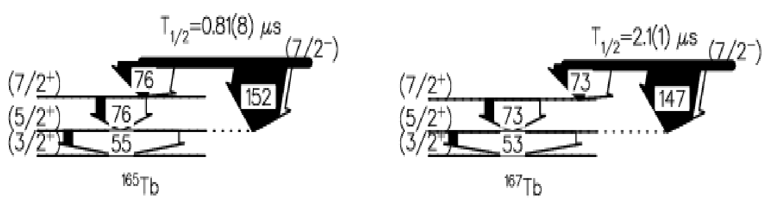

Fig. 4. Tentative level schemes of ^{165}Tb and ^{165}Tb populated in the isomeric decays reported in the current work.

From the reported systematics of lighter, prolate-deformed odd-A Tb isotopes, ^{161}Tb and ^{163}Tb [4, 5], the likely ground state spin/parities for ^{165,7}Tb are $I^\pi = \frac{3}{2}^+$ for both. These are associated with the occupation of the $\frac{3}{2}^+$[411] orbital and consistent with the predictions of equilibrium deformation calculations for axially-symmetric, prolate-deformed nuclei as reported by Jain *et al.* [1] and Nazarewicz *et al.* [2]. The other favoured, odd-proton configurations predicted to lie close to the Fermi surface for $Z = 65$ are associated with the $\frac{5}{2}^+$[413], $\frac{7}{2}^-$[523] and $\frac{9}{2}^+$[404] Nilsson deformed single-particle states. The isomeric nature of the observed states and deduced partial level schemes for ^{165}Tb and ^{167}Tb are consistent with hindered decays from an isomeric state to rotational states built on the (likely) positive parity $\frac{3}{2}^+$ ground state. The most probable candidate for the isomeric states would then be the $\pi\frac{7}{2}^{-}[523]$ orbital which would require a (naturally) hindered E1 decay to the positive parity states built on the ground state configuration.

3. Conclusions

In-flight fission of ^{238}U has been used to synthesise the neutron-rich deformed nuclei ^{165}Tb and ^{167}Tb. The first published information on excited states in these systems is presented in the current work following isomer-delayed gamma-ray spectroscopic analysis. In both systems, one-quasi-proton isomeric states with $I^{\pi} = (\frac{7}{2}^{-})$ states are identified in these prolate deformed nuclei with decay half-lives of $T_{1/2} = 0.81(8)$ μs and $T_{1/2} = 2.1(1)$ μs in ^{165}Tb and ^{167}Tb respectively. The deduced level schemes are consistent with E1 multipolarity decays from these metastable states built on the $\frac{7}{2}^{-}[523]$ one quasi-proton states, which decay through rotationally-coupled states built on the deformed $\pi\frac{3}{2}^{+}[411]$ ground state configuration.

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