Title	**Isomer-delayed gamma-ray spectroscopy of neutron-rich 166Tb**
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Citation	**ND 2016: International Conference on Nuclear Data for Science and Technology, Bruges, Belgium, 11–16 September 2016. In EPJ Web of Conferences, 2017, v. 146, absract no. 10009:1-4**
Issued Date	**2017**
URL	**http://hdl.handle.net/10722/252111**
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EPJ Web of Conferences **146**, 10009 (2017) DOI: 10.1051/epjconf/201714610009
ND2016

Isomer-delayed gamma-ray spectroscopy of neutron-rich ^{166}Tb

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Abstract. This short paper presents the identification of a metastable, isomeric-state decay in the neutron-rich odd-odd, prolate-deformed nucleus ^{166}Tb. The nucleus of interest was formed using the in-flight fission of a 345 MeV per nucleon ^{238}U primary beam at the RIBF facility, RIKEN, Japan. Gamma-ray transitions decaying from the observed isomeric states in ^{166}Tb were identified using the EURICA gamma-ray spectrometer, positioned at the final focus of the BigRIPS fragments separator. The current work identifies a single discrete gamma-ray transition of energy 119 keV which de-excites an isomeric state in ^{166}Tb with a measured half-life of 3.5(4) μs. The multipolarity assignment for this transition is an electric dipole and is made on the basis internal conversion and decay lifetime arguments. Possible two quasi-particle Nilsson configurations for the initial and final states which are linked by this transition in ^{166}Tb are made on the basis of comparison with Blocked BCS Nilsson calculations, with the predicted ground state configuration for this nucleus arising from the coupling of the $\nu\frac{1}{2}^{-}[521]$ and $\pi\frac{3}{2}^{+}[411]$ Nilsson orbitals.

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1. Introduction

The valence maximum nucleus ^{170}Dy$_1$04 lies in the centre of the deformed region of prolate nuclear rotors [1]. The particular details of which nuclear orbitals lie close to the Fermi surface and how they influence the evolution of nuclear shapes can be studied by investigating the structure of odd-A and odd-odd nuclei close to the even-even valence maximum core. The present work presents information on the possible single-particle structures which are formed via proton-neutron deformed Nilsson orbital couplings in the Z = 65, N = 101 nucleus ^{166}Tb$_1$01. Prior to this work, the only information available was on the excited states of ^{166}Tb were identified following the β^- decay of the ^{166}Gd mother nucleus, in which discrete energy gamma-ray transitions with energies 40, 119, 158, 536, 976 and 1016 keV identified [2].

2. Experimental details, analysis and results

Neutron-rich nuclei in the vicinity ^{170}Dy were produced following the projectile fission of a 345 MeV per nucleon ^{238}U primary beam on a 2 mm thick berylium production target at the Radioactive Isotope Beam Factory (RIBF) [3], RIKEN, Japan. The typical primary beam current was 10 pnA and the produced fission fragments were transported and separated on an event-by-event basis using the BigRIPS fragment separator at RIKEN [4,5]. The transported ions were identified event-by-event through the separator using the measured magnetic rigidity ($B\rho$), Time-of-Flight (ToF) and energy loss (ΔE) parameters.

The secondary beam fragments were finally brought to rest in the Wide-range Active Silicon Strip Stopper Array (WAS3ABI) [6] which was placed at the final focus of the BigRIPS separator. This position sensitive detector allowed direct correlations with individual implanted ions and also with subsequent β-decay events in the same location of the stopper arising from the same ion [1]. Discrete-energy gamma-ray decays emitted from the implaned ions (following either isomeric decay or β^- decay) were measured using the Euroball RIKEN Cluster Array (EURICA) consisting of 84 coaxial high-purity germanium (HPGe) detectors, arranged in an array of 12 × 7 element CLUSTER detector modules, complemented by 18 additional $LaBr_3$(Ce) detectors for fast-timing measurements [1,7–10]. Related studies from the same experiment have been reported for isomeric and decay spectroscopy of ^{170}Dy and ^{172}Dy [1,10].

Two magnetic rigidity ($B\rho$) settings for the BigRIPS separator were used in the current work. The first was centred on the transmission of fully-stripped ^{170}Dy ions and ran for 13.5 hours of primary beam time [1] with a second setting focused on the transmission of ^{172}Dy [10] which ran for 45 hours of primary beam-time. Figure 1 shows the particle identification plot for the transmitted ions centred on the transmission of ^{172}Dy with the ^{166}Tb species clearly identified. Note that both hydrogen-like (Z = Q-1) and fully-stripped (Z = Q) ions of ^{166}Tb are transmitted in this particular magnetic rigidity setting.

Figure 2 shows the gamma-ray spectrum gated on ^{166}Tb, with the gamma rays measured between 0.2 and 5.0 μs of the implantation of the ions in WAS3ABI. The spectrum shows a discrete transition at energy 119 keV

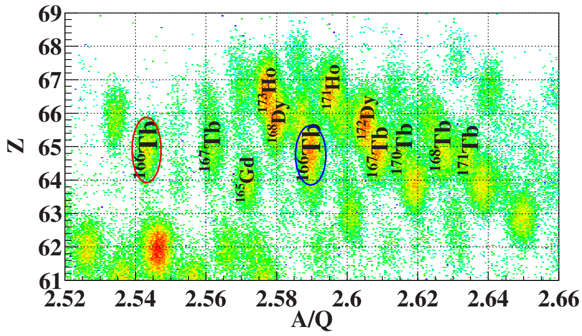

Figure 1. Particle identification plot obtained from the BigRIPS setting centred on ^{172}Dy identifying both the hydrogen-like (blue) and fully-stripped (red) ^{166}Tb ions.

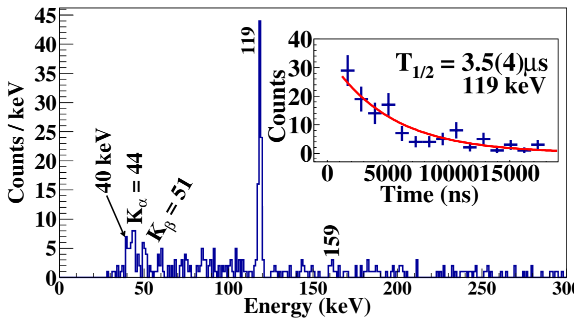

Figure 2. The total projection spectrum of gamma-ray energy from ^{166}Tb emitted with time condition window from 200 ns to 5 μs.

with additional counts associated with the Tb K_α and K_β X rays. The time distribution of the 119 keV gamma ray relative to the implantation time is shown in the inset of Fig. 2. A single component exponential decay function fit to this decay curve results in a half-life for the isomeric state of 3.5(4) μs. We note that the identified gamma-ray transition at 119 keV in the present work was previously noted in the study of the β^- decay of ^{166}Dy by Ichikawa et al., [2]. This previous work interpreted the 119 keV transition decaying from an excited state at excitation energy 158 keV, with a parallel decay branch with similar intensity associated with a transiton at 158 keV. The 119 keV transition was also reported as being in coincidence with a 40 keV gamma ray which fed the proposed ground state of ^{166}Tb. While the 40 keV transition is not clearly separated in the current work, there are counts to the left of the K_α X-rays identified in Fig. 2 which are consistent with a transition at that energy. There is also a weakly populated peak in the region 158 keV in Fig. 2, which is consistent with the reported low-lying level scheme for ^{166}Tb proposed by Ichikawa et al., [2].

Assuming the majority of the branching for the direct decay of the observed isomeric state is via the 119 keV line, its multipolarity can be deduced by comparing the intensity of the terbium K X-rays in the isomer delayed spectrum and the corresponding electromagnetic transition rate for the 119 keV decay. If the K X-rays arise from the competing internal conversion branch of the 119 keV transition from the isomer, this suggests an electric dipole multipolarity for the 119 keV gamma ray, since other likely multipolarities (M1, E2 and M2) all have much higher internal conversion coefficients and would

Table 1. The calculated internal conversion coefficients, Weisskopf single-particle half-life estimates and transition probabilities assuming a half-life of 3.5(4) μs for possible multipolarities of the 119 keV transition in ^{166}Tb. The internal conversion values were estimated using the BRICC code [11].

Multipolarity	α_K (119 keV)	α_{tot} (119 keV)	$T_{\frac{1}{2}}$ (1 W.u)	$B(\sigma\lambda)$ (Wu)
E1	0.16	0.19	1.3×10^{-13}s	3.8(4) $\times10^{-8}$ Wu
E2	0.72	1.39	4.3×10^{-7}s	1.2(1) $\times10^{-1}$ Wu
M1	1.13	1.34	1.6×10^{-12}	4.5(4) $\times10^{-7}$ Wu
M2	8.42	11.1	4.3×10^{-5}	1.2(1) $\times10^{1}$ Wu

have correspondingly more intense X-ray intensities. The theoretical internal conversion coefficients for the likely multipolarities are given in Table 1, using the BRICC code [11].

The measured half-life of the isomeric state is also most consistent with an E1 decay for the 119 keV transition, with the extracted B(E1) transition probability 3.8(4) $\times10^{-8}$ Wu consistent with other hindered E1 decays in this deformed region [12].

3. Possible configurations for the isomeric state in ^{166}Tb

The low-lying Nilsson configurations in ^{166}Tb can be investigated by looking at the single quasi-proton and quasi-neutron Nilsson states which have been identified in the neighboring odd-A terbium (for protons) and N = 101 (for neutrons) nuclei. In general, the lowest-lying Nilsson state, which corresponds to the ground state in the lighter odd-Z Tb isotopes is associated with the $\pi\frac{3}{2}^+$[411] orbitals. The next lowest-lying excited states associated with intrinsic single-particle states are then linked to the $\pi\frac{7}{2}^-$[523], $\pi\frac{5}{2}^+$[413] and $\pi\frac{5}{2}^-$[532] orbitals respectively [13].

The neutron Nilsson orbitals which are expected to lie closest to the Fermi surface for the prolate deformed, axially symmetric N = 101 isotones are the $\frac{1}{2}^-$[521], $\frac{5}{2}^-$[512] and $\frac{7}{2}^+$[633] states [13], which make up the first three intrinsic states observed in the N = 101 isotone ^{169}Er [14]. The lowest lying expected two-quasi-particle states in ^{166}Tb would then be expected to arise from the coupling of these combinations of proton and neutron Nilsson orbitals, with both maximum and minimum K couplings (i.e., $K = \Omega_1 + \Omega_2$ and $K = |\Omega_1 - \Omega_2|$ present).

For ^{166}Tb, the lowest-energy configurations, in the absence of residual proton-neutron interactions associated with the Gallagher-Mozkowski coupling rules, would be expected to arise from the $\pi\frac{3}{2}^+[411]\otimes\nu\frac{1}{2}^-[521]$ configurations, resulting in $K^\pi = 1^-$ and 2^- states, one of which is the most likely candidate for the ground state. The $K^\pi = 1^-$ is favoured considering the expected residual interaction associated with the anti-aligned intrinsic spins between these two orbitals.

From consideration of the neighboring odd-A isotopes, the next most likely proton-neutron 2 quasi-particle couplings would arise from the $\pi\frac{3}{2}^+[411]\otimes\nu\frac{5}{2}^-[512]$ configurations which forms $K = 1^-$ and 4^- states, with the maximally aligned $K = 4^-$ favoured by residual interactions; and the $\pi\frac{3}{2}^+[411]\otimes\nu\frac{7}{2}^+[633]$ which results in $K = 2^+$ and 5^+ states, with the $K = 5^+$ favoured. The observed 119 keV E1 isomeric decay could then arise from the $\Delta K = 1$ single-particle transition between the $K = 5^+$ and $K^\pi = 4^-$ states from the $\pi\frac{3}{2}^+[411]\otimes\nu\frac{7}{2}^+[633]$ to $\pi\frac{3}{2}^+[411]\otimes\nu\frac{5}{2}^-[512]$ configurations, respectively. The reported energy difference of 159 keV between the $\nu\frac{5}{2}^-[512]$ ($E_x = 92$ keV) and the $\nu\frac{7}{2}^+[633]$ ($E_x = 243$ keV) single-particle configurations in the neighboring N = 101 isotone ^{169}Er is similar to the observed 119 keV transition in the current work. The current data does not provide any information on the ordering of these possible initial and final states, which could be reversed and would result in the same isomeric decay. In this scenario, the direct decay from either the $K^\pi = 5^+$ or $K^\pi = 4^-$ configuration to the proposed negative-parity $K^\pi = 1^-$ ground state via a 40 keV M4 or M3 decay, which would result in very long-lived metastable state. This is not consistent with the observations in the current work and the previous study of Ichikawa et al., [2] which show the 119 keV and 40 keV transitions in coincidence. A more consistent candidate for the observed E1 decay is between the $K^\pi = 2^+$ unfavoured coupling of the $\pi\frac{3}{2}^+[411]\otimes\nu\frac{7}{2}^+[633]$ configuration and the unfavoured by $K = 2^-$ coupling of the proposed $\pi\frac{3}{2}^+[411]\otimes\nu\frac{1}{2}^-[521]$ ground state configuration. This $K = 2^-$ state, could then decay by an unhindered M1 to the favoured $K = 1^-$ coupling of the same configuration, which could correspond to the ground state of ^{166}Tb.

Blocked BCS Nilsson calculations were also performed for ^{166}Tb using neutron and proton pair-

Table 2. The configurations of the low-lying two-quasiparticle states in ^{166}Tb predicted by the Nilsson blocked BCS – calculations, using neutron and proton pairing strengths of $G_n = 20.00/A \cdot$ MeV and $G_p = 21.00/A \cdot$ MeV, respectively and quadrupole deformation parameters of $\epsilon_2 = 0.275$ and $\epsilon_4 = 0.027$ with axial symmetry [15,16]. Note that these calculations do not include any adjustments for residual proton-neutron interactions.

K^π	Nilsson Configuration	Energy, (keV)
$2^-, 1^-$	$\pi\frac{3}{2}^+[411]\otimes\nu\frac{1}{2}^-[521]$	0
$3^-, 2^-$	$\pi\frac{5}{2}^+[413]\otimes\nu\frac{1}{2}^-[521]$	273
$4^+, 3^+$	$\pi\frac{5}{2}^-[532]\otimes\nu\frac{1}{2}^-[521]$	314
$3^+, 2^+$	$\pi\frac{5}{2}^-[532]\otimes\nu\frac{1}{2}^-[521]$	355
$5^+, 2^+$	$\pi\frac{3}{2}^+[411]\otimes\nu\frac{7}{2}^+[633]$	62
$6^+, 1^+$	$\pi\frac{5}{2}^+[413]\otimes\nu\frac{7}{2}^+[633]$	335
$7^-, 0^-$	$\pi\frac{7}{2}^-[523]\otimes\nu\frac{7}{2}^+[633]$	376
$6^-, 1^-$	$\pi\frac{5}{2}^-[532]\otimes\nu\frac{7}{2}^+[633]$	417
$4^-, 1^-$	$\pi\frac{3}{2}^+[411]\otimes\nu\frac{5}{2}^-[512]$	145
$5^-, 0^-$	$\pi\frac{5}{2}^+[413]\otimes\nu\frac{5}{2}^-[512]$	418
$6^+, 1^-$	$\pi\frac{7}{2}^-[523]\otimes\nu\frac{5}{2}^-[512]$	459
$5^+, 0^+$	$\pi\frac{5}{2}^-[523]\otimes\nu\frac{5}{2}^-[512]$	501

ing strengths of $G_n = 20.00/A{\cdot}MeV$ and $G_p = 21.00/A{\cdot}MeV$, respectively [13], together with quadrupole deformation parameters of $\epsilon_2 = 0.275$ and $\epsilon_4 = 0.027$. The results of the calculations are presented in Table 2, with the predicted ground state having the expected $\nu\frac{1}{2}^-[521] \otimes \pi\frac{3}{2}^+[411]$ configuration and the next lowest state being the positive parity $K^\pi = 5^+$ and 2^+, $\nu\frac{7}{2}^+[633] \otimes \pi\frac{3}{2}^+[411]$ configuration. Note that these calculations do not include any effects associated with residual proton-neutron interactions. The calculations support the possible interpretations described above.

4. Conclusions

Isomer-delayed spectroscopy has been performed on the neutron-rich, odd-odd prolate deformed nucleus ^{166}Tb at the RIBF facility, RIKEN following the production of this isotope via high-energy projectile fission. The data show evidence for the direct decay of an 119 keV electric dipole transition from the isomeric state, which has a measured half-life of 3.5(4) μs. Possible Nilsson configurations for the initial and final states which are linked by the 119 keV transition are proposed, based on comparison with neighboring odd-A nuclei and BCS-Nilsson calculations. The favoured interpretation for the observed, direct 119 keV E1 transition depopulating the isomer is that it arises from the decay between the $K^\pi = 2^+, \pi\frac{3}{2}^+[411] \otimes \nu\frac{7}{2}^+[633]$ and the $K^\pi = 2^-, \pi\frac{3}{2}^+[411] \otimes \nu\frac{1}{2}^-[521]$ configurations, the latter of which decays by a 40 keV M1 to the predicted $K^\pi = 1^-$ $\pi\frac{3}{2}^+[411] \otimes \nu\frac{1}{2}^-[521]$ ground state configuration.

The authors are indebted to the facility crews who provided the beams at RIBF, operated by RIKEN Nishina Center and CNS, University of Tokyo, the EUROBALL Owners Committee for the loan of germanium detectors, the PreSpec Collaboration for the use of the readout electronics. Part of the WAS3ABi was supported by the Rare Isotope Science Project which is funded by MSIP and NRF of Korea. This work is supported by the UK Science and Technology Facilities Council (STFC); the UK National Measurement Office (PHR); JSPS KAKENHI Grant No. 24740188, 25247045, and 25287065; the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contract No. DE-AC02-06CH11357 (FGK) NRF Korea Grants No.2009-0093817 and 2013R1A1A2063017 (CSL), 2015R1D1A1A01056918, 2016R1A5A1013277 and 2016K1A3A7A09005579 (KYC); the Hungarian Research Fund OTKA contract number K100835 and Science Foundation Ireland under Grant No. 12/IP/1288 (OJR).

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