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Decay properties of long-lived isomers in the odd-odd $N = 81$ nucleus ^{146}Tb compared to the ^{148}Ho and ^{150}Tm nuclei

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Excited states of the ^{146}Tb nucleus have been studied using γ-ray and electron spectroscopy in off-beam and in-beam modes following ^{112}Sn(^{40}Ar,3n3p) reaction with the use of the OSIRIS-II, HPGe detector array and the conversion electron spectrometer. The multipolarity of the 343 keV transition deexciting the (7$^-$) level in ^{146}Tb shows mainly an $E2$ nature and the first excited state above the 23 s isomer is assigned as a (5$^-$, 6$^-$) state. The log ft values have been deduced for 11 β^+/EC transitions populating excited states in ^{146}Gd. The systematic behavior of spins and parities of the long-lived levels at $0 + x$ keV and the first excited states above them in the $N = 81$ isotones ^{146}Tb, ^{148}Ho, and ^{150}Tm is discussed.

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The odd-odd $N = 81$ isotones located above the $Z = 64$ semiclosed shell have two long-lived states deexcited by the β^+/EC decay [1], one with $I^\pi = 1^+$, the other with $I^\pi = (5^-$ or $6^-)$ [2–4]. The aim of this work is to provide arguments for spin and parity assignment to states below 10^+ isomers in these nuclei.

Levels in the nucleus ^{146}Tb have been populated in the ^{112}Sn(^{40}Ar,3p3n) reaction at a beam energy of 232 MeV. The beam was provided by the cyclotron of the Heavy Ion Laboratory, University of Warsaw. In the experiment, 11 HPGe detectors of the OSIRIS-II array were operated together with an electron spectrometer [6].

The half-life of the 10^+ isomer in ^{146}Tb has been reinvestigated and the obtained time spectra of the 417, 343, 205, and 157 keV transitions are shown in Fig. 1. A half-life of 1.24 ± 0.03 ms for the 10^+ level was obtained as a weighted average of the values for these lines. This half-life is in reasonable agreement with that deduced by Broda *et al.* [2,3], viz. $T_{1/2} = 1.18 \pm 0.02$ ms.

Measurements of conversion electrons in an off-beam mode [6] were performed in order to deduce multipolarity assignments for specific transitions in the decay path of the 10^+ isomer observed [2] in the ^{146}Tb nucleus. Electron spectra for the 417 keV line gated on the 343 keV γ ray, and for the 343 keV line gated on the 417 keV γ ray in ^{146}Tb are shown in Fig. 2 (see also level scheme in Fig. 3). From the obtained conversion coefficients given in Table I it was concluded that the 417 keV transition in ^{146}Tb is of an $E3$ character—in agreement with the former [2,3] assumption based on a conversion coefficient estimated from the intensity balance.

The electron conversion coefficient for the 343 keV transition measured in the present work indicates an $E2$ nature for this transition with about 25% admixture of the $M1$ multipolarity (the mixing ratio δ^2 calculated from the internal conversion coefficient is equal to $2.8 \pm {}^{\infty}_{1.9}$). The experimental data (in the limits of standard deviation) do not exclude the pure $E2$ transition, therefore it is proposed that the spin and parity (5$^-$, 6$^-$) can be assigned to the level placed 19 keV above the 23 s, $0 + x$ keV isomer in the ^{146}Tb nucleus (Fig. 3) (and not solely 6$^-$ as assumed in Refs. [2,3,7–9]). The 205, 157, and 138 keV transitions remain of $M1$ character—in agreement with the assumption in Ref. [3].

In order to obtain additional support for the $I^\pi = 5^-$ assignment to the 23 s, $0 + x$ keV isomer in ^{146}Tb the log ft values for its β^+/EC decay to the levels in the daughter nucleus ^{146}Gd [10] have been reinvestigated and extended. For this purpose, γ-ray singles and coincidence spectra were measured during the beam-off periods of the cyclotron beam. Its macrobeam structure was utilized giving beam-off time intervals of 4–8 ms. From the intensities of γ transitions in ^{146}Gd, the β^+/EC-feeding intensities have been evaluated as shown in Table II. The difference between the initial and final atomic mass energies, i.e., the Q_{EC} value = 8267(45) keV (ground state to ground state), was taken from Refs. [4,10]. The log ft values have been deduced for 11 β^+/EC transitions populating excited states in ^{146}Gd.

Most probably, the β^+/EC decay of the 23 s isomer in ^{146}Tb does not directly proceed to the 1579 keV, 3$^-$ level in ^{146}Gd. One can guess that the feeding to this level is smaller than the observed 6.9% due to undetected γ rays, and consequently the log ft value is >6.1. In the measured spectra a weak 1972 keV, $2^+ \to 0^+$ ground-state transition (also observed in Ref. [10]) has been found to be in coincidence with the 1059 keV, $3^+ \to 2^+$ and 193 keV, $0^+ \to 2^+$ transitions deexciting the 3031 and 2165 keV levels in ^{146}Gd known from the decay of the 8 s,

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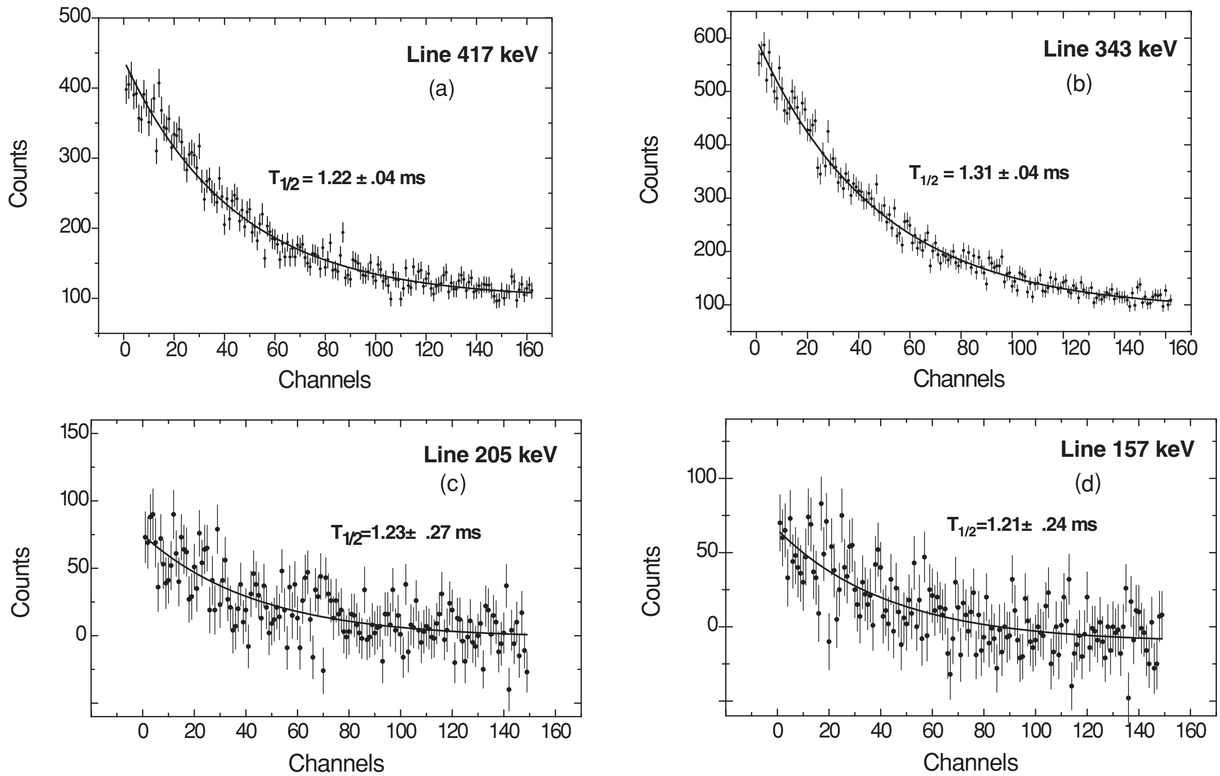

FIG. 1. Time spectra for the (a) 417, (b) 343, (c) 205, and (d) 157 keV γ rays in the decay of the (10^+) isomer in ^{146}Tb measured in the off-beam periods lasting 3.5 ms. A half-life of 1.24 ± 0.03 ms for the 10^+ level was obtained as a weighted average of the values for these lines.

1^+ ground state of ^{146}Tb. Therefore assuming that the ground state in ^{146}Tb is also populated in the used reaction, the log ft value to the 1972 keV level should be larger than the deduced value of 7.

The estimated log ft values are shown in Table II. Especially crucial for further discussion are the β^+/EC decays of the 23 s isomer in ^{146}Tb to 4^- (2996 keV and 4719 keV), 5^- (2658 keV and 4828 keV), and 6^- (3099 keV) states in the ^{146}Gd daughter nucleus (see partial decay scheme of the 23 s ^{146}Tb isomer, Fig. 4). Low measured log $ft \sim 5$ values suggest the allowed character of β^+/EC transitions, therefore the selection rules indicate spin and parity 5^- for the 23 s, $0 + x$ keV level in ^{146}Tb. The present results for β^+/EC decay of the 23 s isomer in ^{146}Tb confirm the earlier findings of Ref. [10].

It is worthwhile to notice that the decay of the (7^-) state in ^{148}Ho (Fig. 3) to (6^-), $x + 141$ keV and to (5^-), $x + 0$ keV states is very similar to the decay of the (7^-) state in ^{146}Tb leading to (6^-), $x + 157$ keV level and to the above-discussed $(5^-, 6^-)$, $x + 19$ keV state. This can imply that the $x + 19$ keV state in ^{146}Tb, the long-lived 5^- isomer in ^{148}Ho, and the ground state (g.s.) in ^{150}Tm may have a similar nature. The 2.2 s g.s. in ^{150}Tm was assigned in Refs. [2,3,5] as (6^-), differently than the decay pattern of the (7^-) states in ^{146}Tb and ^{148}Ho nuclei. There is no definite experimental proof for the spin and parity assignment of known levels in the ^{150}Tm nucleus. Therefore, the spin and parity of the 2.2 s g.s. in ^{150}Tm remains (6^-) as was assumed in Refs. [2,3,5] (see Fig. 3). Future experiments are needed to answer this question.

TABLE I. Properties of the conversion electron lines assigned to $^{146}_{65}$Tb$_{81}$: γ-ray energies E_γ, experimental and theoretical $K/L + M + \cdots$ ratios and conversion coefficients α_K as well as $\alpha_{L+M+\cdots}$ are given.

E_γ [keV]	Shell	α_{exp}[a] $K/(L+M+\cdots)$	Theory[b] $E1$	$E2$	$M1$	$E3$	Multipolarity
343	α_K	0.040(8)	0.010	**0.032**	**0.062**	0.094	$E2$ or $M1 + E2$
	$\alpha_{L+M+\cdots}$	0.008(2)	0.002	**0.009**	**0.011**	0.058	
	$K/(L+M+\cdots)$	5.0(16)	5.682	**3.447**	**5.565**	1.617	
417	α_K	0.047(9)	0.006	0.019	0.037	**0.051**	$E3$
	$\alpha_{L+M+\cdots}$	0.025(7)	0.001	0.005	0.007	**0.024**	
	$K/(L+M+\cdots)$	1.9(5)	5.745	3.887	5.588	**2.110**	

[a]Present experiment.
[b]Theoretical values are from [12].

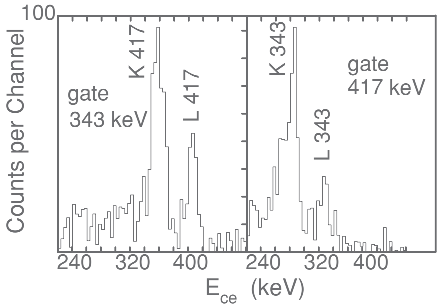

FIG. 2. Off-beam background-corrected e^- spectra gated on the 343 and 417 keV γ rays in ^{146}Tb. The quantity E_{ce} stands for conversion electron lines energy.

The 23 s isomer in ^{146}Tb was proposed [2,3] to be dominant of the $[\pi h_{11/2}, \nu d_{3/2}^{-1}]5^-$ character with a probable admixture of a $\pi h_{11/2}\nu s_{1/2}^{-1}$ configuration. We suggest that the 343 keV transition proceeds from a $[\pi h_{11/2}, \nu d_{5/2}^{-1}]7^-$ to a $[\pi h_{11/2}, \nu s_{1/2}^{-1}]5^-$ state. A $\pi h_{11/2}, \nu d_{3/2}^{-1}$ configuration has been assigned to the intermediate $x + 157$ keV, 6^- level.

Based on a comparison of the decay pattern of 7^- states in ^{146}Tb, ^{148}Ho, and ^{150}Tm, it is also tempting to consider the possibility of spin and parity 5^- [1] for the 2.2 s g.s. in ^{150}Tm. Assuming the valence nucleons configuration as given above one can calculate the ratios of reduced transition probabilities of transitions deexciting the 7^- level, $B(M1, 7^- \to 6^-)/B(E2, 7^- \to 5^-)$, for $^{146}_{65}$Tb, $^{148}_{67}$Ho, and $^{150}_{69}$Tm. They were calculated as

$$\frac{B(M1; I \to I-1)}{B(E2; I \to I-2)} = \frac{0.693[E_\gamma(I \to I-2)]^5}{[E_\gamma(I \to I-1)]^3 \lambda(1+\delta^2)} \left(\frac{\mu_N}{eb}\right)^2,$$

where energies are in units of MeV. Mixing ratios of $\delta = 0$ for $\Delta I = 1$ transitions were assumed in the data analysis and the experimental branching ratios λ were deduced from the relative γ-ray intensities in the spectra. In the case of ^{150}Tm, the branching ratio was taken from Ref. [3] and for ^{148}Ho from Ref. [11]. The experimental $B(M1)/B(E2)$ ratios are given in Table III and are compared with estimated ratios of reduced transition probabilities between two-quasiparticle states: $[\pi h_{11/2}, \nu d_{5/2}^{-1}]7^-$ to $[\pi h_{11/2}, \nu d_{3/2}^{-1}]6^-$ and $[\pi h_{11/2}, \nu d_{5/2}^{-1}]7^-$ to $[\pi h_{11/2}, \nu s_{1/2}^{-1}]5^-$. For a transition between two 2-particle states $(j_1 j_2)J$ and $(j_1' j_2')J'$ in an odd-odd nucleus, one can deduce [13] the following relation:

TABLE II. The β^+/EC decay of the 5^-, 23 s isomer in ^{146}Tb populating particle-hole excitations in the daughter nucleus ^{146}Gd. The energies, spins, and the deduced β^+/EC feeding intensities of levels in ^{146}Gd and log ft values obtained in the present experiment as well as in the former work [10] are given.

E_{level} [keV]	I^π_{final}	$I_{\beta^+/\text{EC}}$ % feed	log ft this exp.	log ft [10]
1579.5	3^-	<6.9	>6.1	>6.0
1972.0	2^+	<2.0	>7.0	
2611.4	4^+	3.0	6.09(15)	
2658.4	5^-	42.4	4.92(0.1)	∼4.9
2982.4	7^-	<2.0	>6.12	
2996.6	4^-	15.1	5.24(0.05)	∼5.2
3099.4	6^-	12.1	5.29(0.05)	∼5.1
3313.4	5^-	3.0	5.81(0.09)	
3423.1	3^-	<3.0	>5.77	
4719.2	4^-	6.0	4.88(0.06)	∼4.5
4828.5	5^-	2.0	5.30(0.12)	∼5.5

$$\begin{aligned} B(EL, ML) &= 1/(2J+1)|\langle J'||(EL, ML)||J\rangle|^2 \\ &= (2J'+1)\Bigg[(-1)^{j_1'+j_2'+J+L}\begin{Bmatrix} j_1 & j_2 & J \\ J' & L & j_1' \end{Bmatrix} \\ &\quad \times \langle j_1'||(EL, ML)||j_1\rangle \delta_{j_2', j_2} + (-1)^{j_1+j_2+J'+L} \\ &\quad \times \begin{Bmatrix} j_1 & j_2 & J \\ L & J' & j_2' \end{Bmatrix} \langle j_2'||(EL, ML)||j_2\rangle \delta_{j_1', j_1}\Bigg]^2, \end{aligned}$$

where L stands for multipolarity of the transition. For example for the electric quadrupole transition:

$$B(E2) = 1/(2J+1)|\langle J'||\Sigma e_{\text{eff}} r^2 Y_2||J\rangle|^2,$$

where e_{eff}/e is assumed to be 1. The radial integrals $\langle r^2\rangle$ were calculated by use of the Woods-Saxon wave functions, given in Ref. [13]. The experimental and calculated $B(M1)/B(E2)$ ratios agree well for ^{146}Tb. For ^{148}Ho the experimental value is about four times larger than the calculated one

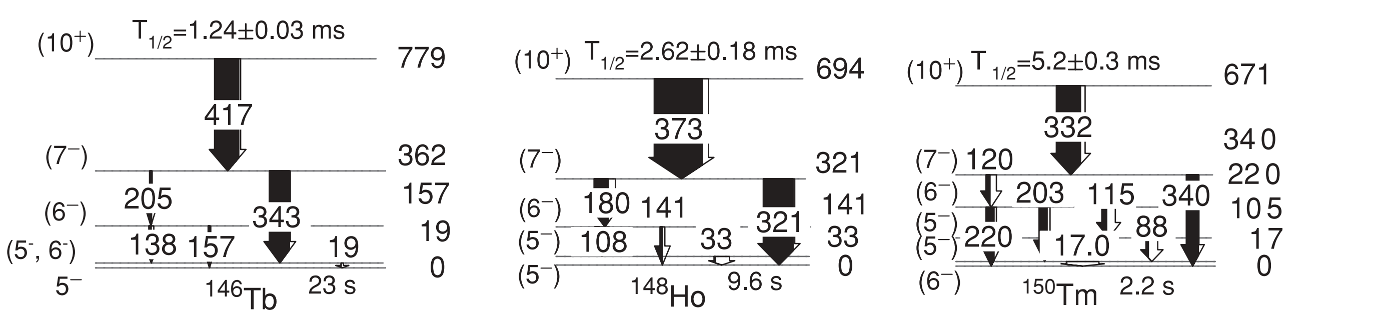

FIG. 3. Decay schemes of the (10^+) isomers in the $N = 81$ isotones ^{146}Tb, ^{148}Ho, and ^{150}Tm. The half-life of the (10^+) isomer in ^{146}Tb results from the present experiment, while the value for ^{148}Ho is taken from our former paper [11]. The half-life value of the (10^+) isomer in ^{150}Tm and its decay scheme is taken from Ref. [3]. As the connections of the partial level schemes for ^{146}Tb and ^{148}Ho to the respective ground states are unknown, different values of x for each isotone should be added to the energy of each level.

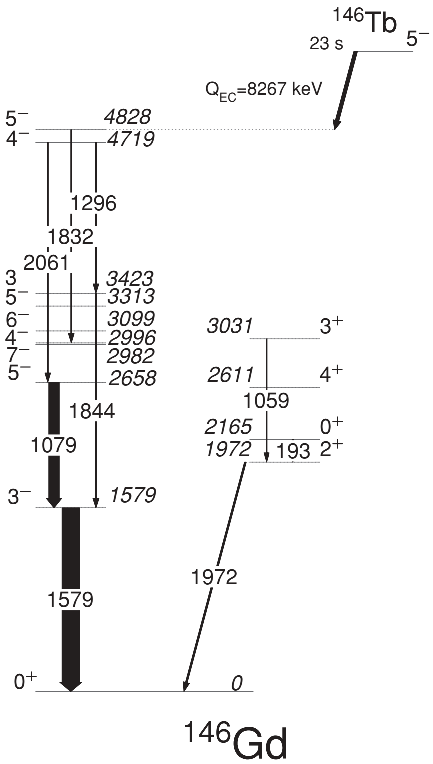

FIG. 4. Partial decay scheme of the 23 s isomer in ^{146}Tb to the excited states in ^{146}Gd [10].

which may result from configuration mixing. The $B(M1;$ 120 keV$)/B(E2;$340 keV) ratio for ^{150}Tm, however, seems to be too high, contradicting the 5^- g.s. assignment. The $E2$ strength [14] should rather increase when approaching the mass number $A = 150$, resulting in smaller $B(M1)/B(E2)$ ratios.

Concluding, the decay properties of 10^+ isomeric states in $N = 81$, ^{146}Tb, ^{148}Ho, and ^{150}Tm nuclei were investigated and discussed. In ^{146}Tb and ^{148}Ho the long-lived isomers (23 s and 9.6 s, respectively) have a spin assignment of 5^-, but the spin

TABLE III. $R = B(M1)/B(E2)$ ratios for 7^- states located below the 10^+ isomers in the $N = 81$ nuclei.

^{A}X	Transitions	R_{exp}	R_{calc}
$^{146}_{65}$Tb	$(7^- \to 6^-)/(7^- \to 5^-)$	0.032	0.034
	(205 keV)/(343 keV)		
$^{148}_{67}$Ho	$(7^- \to 6^-)/(7^- \to 5^-)$	0.190	0.046
	(180 keV)/321 keV)		
$^{150}_{69}$Tm	$(7^- \to 6^-)/(7^- \to 5^-)$	0.932	0.100
	(120 keV)/(340 keV)		

of the 2.2 s g.s. in ^{150}Tm still remains an open question. The allowed log ft [5] values indicate a spin and parity assignment of 4^-, 5^-, or 6^- for the ^{150}Tm parent state. Since 6^+, 7^-, and 8^+ ^{150}Er levels [5] are also observed; so one can favor the (6^-) assignment, however, according to Nolte *et al.* [1], the 4^- or 5^- assignment is suggested, as they did not see γ rays from levels with spins greater than 5. In such a situation it seems perhaps better to keep the (6^-) assignment—until good experimental results for ^{150}Tm become available.

The experiment concerning the ^{150}Tm nucleus should be performed in the future in order to check the electron conversion coefficients of lines deexciting the 10^+ isomer, as well as the γ-ray intensities. Especially interesting is the multipolarity of the 340 keV transition which will be important for the spin and parity assignment of the ^{150}Tm ground state. The log ft values for its β^+/EC decay to the levels in the daughter nucleus ^{150}Er (leading in Refs. [1,5] to a different conclusion concerning the spin of the ^{150}Tm parent state) should also be reinvestigated and extended.

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[1] E. Nolte *et al.*, Z. Phys. A **306**, 223 (1982).
[2] R. Broda *et al.*, Z. Phys. A **316**, 125 (1984).
[3] R. Broda *et al.*, Z. Phys. A **334**, 11 (1989).
[4] E. Newman *et al.*, Phys. Rev. C **9**, 674 (1974).
[5] K. S. Toth *et al.*, Phys. Rev. C **35**, 620 (1987).
[6] J. Andrzejewski *et al.*, Nucl. Instrum. Methods A **585**, 155 (2008).
[7] R. Collatz *et al.*, Z. Phys. A **359**, 113 (1997).
[8] C. Y. Xie *et al.*, Eur. Phys. J. A **19**, 7 (2004).
[9] Krishichayan *et al.*, Phys. Rev. C **70**, 044315 (2004).
[10] J. Styczeń *et al.*, *Proceedings of the International Conference on Nuclei Far from Stability, Helsingør, Denmark, Vol. 2*, edited by P. G. Hansen and G.B. Nielsen (CERN, Geneva, 1981), p. 548.
[11] J. Kownacki *et al.*, Phys. Rev. C **81**, 044305 (2010).
[12] T. Kibédi *et al.*, Nucl. Instrum. Methods A **589**, 202 (2008).
[13] S. Wahlborn and I. Martinson, Arkiv Fysik **31**, 355 (1966).
[14] P. M. Endt, At. Data Nucl. Data Tables **26**, 47 (1981).