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Short Note

Excited states of ^{154}Tm

C. Foin[1], A. Gizon[1], J. Genevey[1,a], J. Gizon[1], P. Paris[2], F. Farget[1,b], D. Santos[1], D. Barnéoud[1], and A. Płochocki[3]

[1] Institut des Sciences Nucléaires, IN2P3-CNRS/Université Joseph Fourier, 38026, Grenoble Cedex, France
[2] CSNSM, IN2P3-CNRS, Bt. 104, 91405 Campus Orsay, France
[3] Institute of Experimental Physics, 00-681, Warsaw, Poland

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Abstract. A high-spin level structure of the nucleus ^{154}Tm has been established for the first time up to 6.14 MeV. The ^{118}Sn + ^{40}Ca reaction at 205 MeV associated with the recoil shadow method was used to identify the $I^{\pi} = (19)^{+}$ isomeric state at 2.74 MeV. In-beam γ-ray and conversion electron spectroscopy have been applied on the ^{144}Sm(^{14}N, 4n)^{154}Tm reaction at 95 MeV to build the level scheme. The level structure of ^{154}Tm is compared to other structures observed in $N = 85$ neighbouring nuclei.

PACS. 21.10.Pc Single-particle levels and strength functions – 23.20.Lv Gamma transitions and level energies – 27.70.+q $150 \leq A \leq 189$

1 Introduction

Neutron-deficient rare-earth nuclei with $N = 87$ neutron number seem to constitute a border between collective and non-collective rotation at low and moderate spins [1]. In the $N = 85$ isotonic chain, several decay schemes have been already established up to 4.6 MeV for ^{149}Gd ($Z = 64$) [2], 12.9 MeV for ^{150}Tb ($Z = 65$) [3], 6 MeV for ^{151}Dy ($Z = 66$) [4], 6 MeV for ^{152}Ho ($Z = 67$) [5], 8.4 MeV for ^{153}Er ($Z = 68$) [6], 2.3 MeV for ^{155}Yb ($Z = 70$) [7], 5.3 MeV for ^{156}Lu ($Z = 71$) [7], 6.5 MeV for ^{157}Hf ($Z = 72$) [8] and discussed in terms of shell model multiplets with respect to the doubly closed-shell nucleus ^{146}Gd ($Z = 64, N = 82$). The odd-odd nucleus ^{154}Tm ($Z = 69$) is a good candidate for studying the nuclear structure of a $N = 85$ nucleus having $\Delta Z = 5$ valence protons.

The knowledge of ^{154}Tm to date is very limited. It has been firmly identified by a recent on-line mass separation [9]. In this study, two isomeric states have been established at low excitation energy in this nucleus, both of them de-exciting by α-decay to ^{150}Ho and by (EC + β^{+}) decay to ^{154}Er. From log(ft) values and α-hindrance factors, the assignments of the high-spin isomer ($T_{1/2} = 3.3$ s) and of the low-spin isomer ($T_{1/2} = 8.1$ s) have been adopted to be 9^{+} and 2^{-}, respectively. The relative position of these two isomers is still unknown.

[a] e-mail: genevey@isn.in2p3.fr
[b] *Present address*: IPNO, IN2P3-CNRS, 91406 Orsay-Cedex, France.

In a systematic search of isomers in neutron-deficient Tm nuclei, applying on-line prompt and delayed γ-γ coincidence techniques for ^{144,147}Sm(^{14}N, xn) reactions at bombarding energies ranging from 80 to 120 MeV, γ-ray cascades were assigned to $^{153\text{-}157}$Tm nuclei [10]. A sequence 471, 279, 745, 578, 351 keV, fed by a high-spin isomeric state was assigned to ^{154}Tm. The very short half-life of this isomer was not measured and the order of the transitions in the cascade was only tentative. Another prompt cascade with lines at 167, 212, 382, 680, 751 keV was assigned to ^{153}Tm. This last sequence was not reported in the detailed level scheme of ^{153}Tm established later up to 9.2 MeV excitation energy using the ^{122}Te(^{35}Cl, 4n) reaction [11].

2 Experimental procedures and results

To study ^{154}Tm, two experiments have been undertaken at the Grenoble variable-energy cyclotron.

In a first experiment, the recoil shadow method (RSM) has been applied to confirm and study the short half-life isomer proposed by Kossakowski *et al.* [10]. The details of the geometrical set-up have been given in a previous paper [12]. In the present work, a $1.5\,\mathrm{mg \cdot cm^{-2}}$ isotopically enriched ^{118}Sn (95.7% enrichment) target was bombarded with a ^{40}Ca beam at 205 MeV. In the fusion-evaporation reaction, ^{154}Tm was produced via the p, 3n exit channel. A thin ($1\,\mathrm{mg \cdot cm^{-2}}$) carbon-catcher stopped the recoil nuclei. The target-catcher time of flight was about 20 ns. Due

Table 1. Properties of transitions identified in ^{154}Tm.

$E_\gamma(\Delta E_\gamma)$ (keV)	I_γ (beam)	I_γ (catcher)	Multi-polarity	Initial level (keV)	Final level (keV)	$E_\gamma(\Delta E_\gamma)$ (keV)	I_γ (beam)	I_γ (catcher)	Multi-polarity	Initial level (keV)	Final level (keV)
89.9(1)	29	$^{b)}$	$M1(E2)$	2514.4	2424.5	578.2(1)	$106^{e)}$	75	$E2$	1323.3	745.1
102.3(1)	37	37	$M1(E2)$	2616.7	2514.4	597.0(2)	21				
125.9(1)	70	82	$E2$	2742.7	2616.7	609.6(3)	9			2424.5	1814.6
138.9(2)	23			2881.5	2742.7	636.2(2)	72		$E2$	4056.9	3420.8
140.6(3)	$^{a)}$			1814.6	1674.0	639.0(2)		$^{b)}$		1674.0	1035.1
159.9(2)	11					639.2(2)	$82^{e)}$		$M1(E2)$	2453.8	1814.6
166.9(1)	122		$E1$	5375.6	5208.7	659.6(2)	46	23	$M1(E2)$	3409.8	2750.2
197.8(2)	20			4865.8	4668.0	667.0(3)	34				
212.0(1)	116		$E2$	5208.7	4996.7	669.6(3)	14			4090.9	3420.8
214.8(3)						678.1(3)			$M1(E2)$	3420.8	2742.7
260.2(2)	21					679.6(3)	$177^{e)}$	49	$E2$	1814.6	1135.0
266.1(2)	26	15		266.1	0.0	699.2(3)	6			2514.4	1814.6
268.9(3)	$52^{b)}$	$59^{b)}$	$M1(E2)$	3740.3	3471.4	721.3(3)	33	4	$E2$	3471.4	2750.2
279.3(1)	88	$140^{c)}$	$M1(E2)$	2424.5	2145.2	745.1(1)	100	100	$E2$	745.1	0.0
290.0(2)	13			1035.1	745.1	751.8(1)	102	74	$E2$	751.8	0.0
296.4(2)	$39^{b)}$	$131^{b)}$	$M1(E2)$	2750.2	2453.8	757.7(2)	73	$65^{d)}$	$M1(E2)$	4498.0	3740.3
330.5(2)	$46^{b)}$	8	$M1(E2)$	3740.3	3409.8	765.5(2)	$133^{b)}$	$50^{d)}$		6141.1	5375.6
335.5(2)	13					769.0(3)	20	$30^{d)}$		1035.1	266.1
350.7(1)	84	96	$M1(E2)$	1674.0	1323.3	802.0(3)	23	17		2616.7	1814.6
358.9(2)	24			3240.3	2881.5	935.6(3)	49	12	$E2$	2750.2	1814.6
383.2(1)	85	62	$E2$	1135.0	751.8	1142.4(3)	24				
395.4(2)	$34^{b)}$			4486.2	4090.9	1175.3(3)	43			4056.9	2881.5
429.3(2)	56		$M1(E2)$	4486.2	4056.9	1257.7(3)	45			4498.0	3240.3
471.2(1)	100	100	$E2$	2145.2	1674.0	1289.9(3)	22			2424.5	1135.0
498.7(1)	75		$E2$	4996.7	4498.0	1348.2(3)	63			4090.9	2742.6
510.4(3)	48			4996.7	4486.2						
577.1(3)				4668.0	4090.9						

$^{a)}$ Observed in coincidence only.
$^{b)}$ Composite.
$^{c)}$ Also in ^{152}Er.
$^{d)}$ Also in ^{153}Er.
$^{e)}$ Sum intensity of two neighbouring peaks.

to the extremely weak ^{154}Tm radioactivity, only singles γ-ray spectra have been recorded in this measurement. The relative γ-ray intensities, I_γ(catcher), are reported in table 1. In addition to the cascade of γ-rays previously assigned to ^{154}Tm [10], three new transitions at 89.9, 102.3 and 125.9 keV have been easily seen. The weakness of γ-ray intensities recorded in the spectrum can be very likely explained by a short half-life of a few nanoseconds for the ^{154m}Tm isomers, the major part de-exciting in flight, before reaching the catcher. One can also note that among the five prompt γ-rays assigned to ^{153}Tm [10], those at 166.9 and 212.0 keV are not seen while very weak lines are observed at 383, 679 and 752 keV (see table 1).

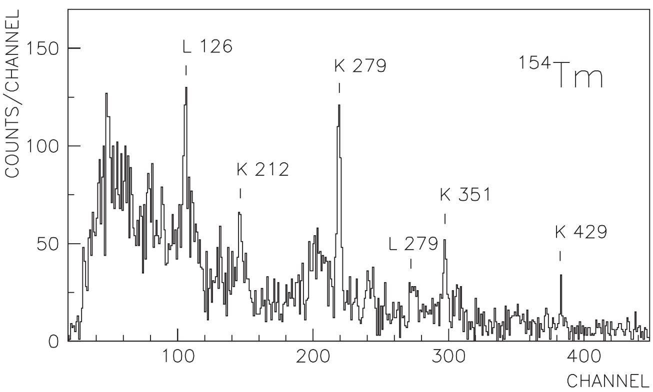

Fig. 1. Example of conversion electron spectrum detected in the γ-e$^-$ coincidence experiment.

In a second experiment, the ^{144}Sm(^{14}N, 4n)^{154}Tm reaction has been used at a bombarding energy of 95 MeV. The experimental set-up and all the geometrical details have been recently described [6]. The conversion electrons were measured by using an electron guide, the Betatronc [13] equipped with a Si(Li) detector. A thin ($250\,\mu$g $\cdot$ cm^{-2}) ^{144}Sm target (87% enrichment) deposited on a $470\,\mu$g $\cdot$ cm^{-2} carbon backing was used after careful adjustments suitable for simultaneous detection of γ- and electron-singles spectra, γ-γ and γ-e$^-$ coincidence spec-

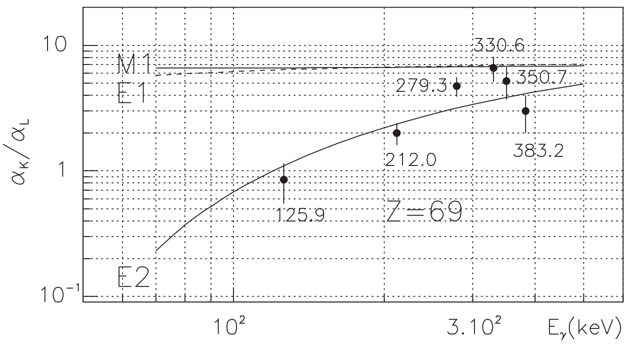

Fig. 2. α_K/α_L ratios for the strongest converted transitions decaying from excited states of ^{154}Tm.

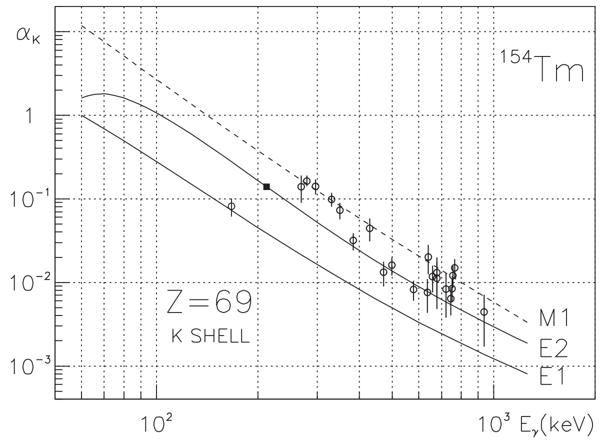

Fig. 3. Absolute α_K conversion coefficients of transitions in ^{154}Tm. The normalization is based on the 212 keV transition (full square).

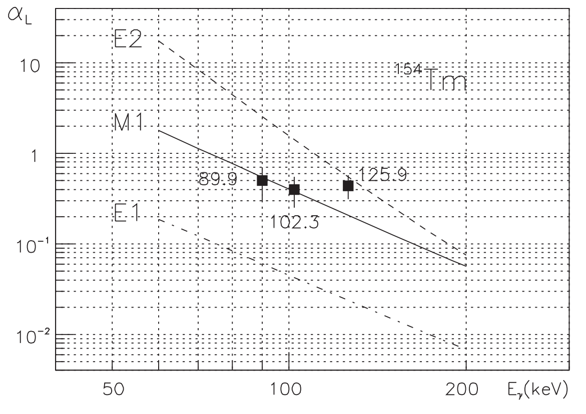

Fig. 4. Absolute α_L conversion coefficients of low-energy transitions in ^{154}Tm.

tra. An example of low-energy electron spectrum is shown in fig. 1. Energies and intensities of the γ transitions assigned to ^{154}Tm are reported in table 1. The precision of the intensities is of order of 10% for the strong γ lines.

From the present study the multipolarities of many γ-rays ranging from 80 keV to 1 MeV in energy have been determined using singles and electron-γ coincidence spectra. Due to the existence of oscillations along the efficiency curve of the Betatronc [13], a precise adjustement of this curve was needed. This has been done experimentally, using the characteristics of the transitions previously known in the neighbouring isotopes produced simultaneously in the nuclear reaction, such as ^{151m}Er, ^{150m}Er, ^{148m}Dy, ^{149m}Dy or in ^{150}Dy reached by β-decay of ^{150}Ho. In addition, for a few strongly converted transitions, α_K/α_L ratios have been estimated from several electron spectra in coincidence with the most intense γ-rays (see fig. 2). Therefore, the transitions at 125.9, 212.0 and 383.2 keV are compatible only with a pure $E2$ multipolarity. The theoretical value $\alpha_K = 0.139$ for the 212.0 keV $E2$ transition has been used as a reference to normalize the conversion coefficients α_K reported in fig. 3. Using simultaneously α_K values and α_K/α_L ratios, $M1$, $E2$ or $M1(E2)$ characters can be assigned to several transitions as those at 279.3, 330.5 or 350.7 keV. Using the same normalization $\alpha_K(212\,\text{keV}) = 0.139$, absolute α_L conversion coefficients have also been extracted for low-energy transitions. As seen in fig. 4, unambiguous $M1$ multipolarities can be deduced for the transitions at 89.9 and 102.3 keV.

3 The level scheme of ^{154}Tm

The proposed level scheme in fig. 5 is mostly established from prompt γ-γ coincidence relationships. For practical reasons, the excitation energy of the 9^+ isomer has been

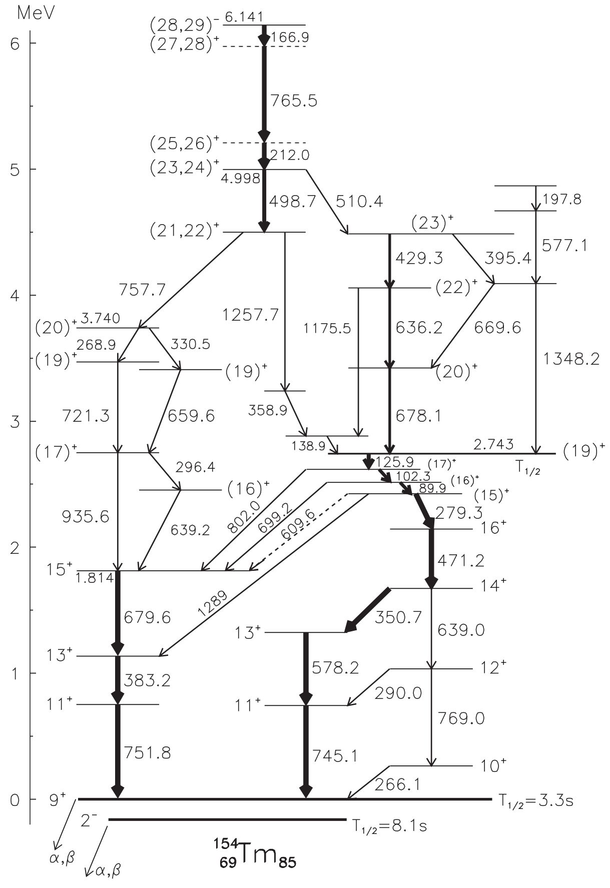

Fig. 5. Level scheme of ^{154}Tm deduced from the present study.

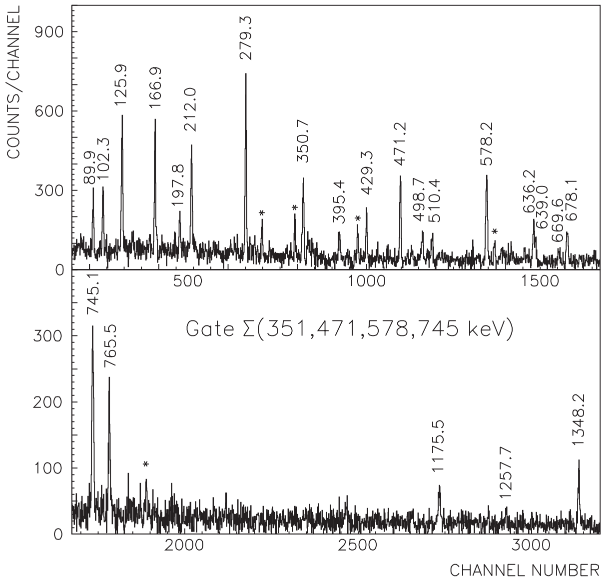

Fig. 6. Sum of γ-γ prompt coincidences spectra gated by the main transitions shown at the right-hand side of the ^{154}Tm level scheme. The asterisks indicate that the γ-rays belong to neighbouring isotopes.

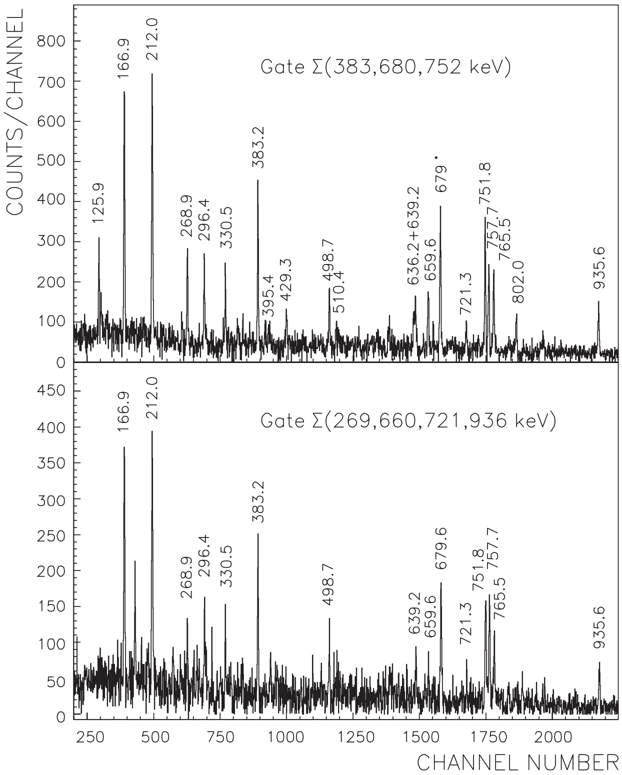

Fig. 7. Examples of γ-γ prompt coincidence spectra used to establish the cascade shown at the left-hand side of the level scheme in fig. 5.

set to zero. The transition multipolarities deduced from internal conversion electron measurements, the intensity balances at each step and the γ-delayed spectrum recorded in the catcher experiment have been decisive.

From γ-γ coincidence spectra analysis, one can distinguish several main groups of γ transitions in the level scheme, as follows:

i) The most important group contains the lines at 745.1, 578.2, 350.7, 471.2 and 279.3 keV, previously identified with a short half-life by Kossakowski *et al.* [10] and three new low-energy lines at 89.9, 102.3 and 125.9 keV. Few less intense transitions at 266.1, 290.0, 639.0 and 769.0 keV, seen from γ-γ coincidences, complete this group placed directly above the $I^\pi = 9^+$ isomer, at the right-hand side in the level scheme (fig. 5). The excited level $I^\pi = (19)^+$ proposed at 2.743 MeV is isomeric because all the transitions above mentioned have been well observed in the delayed γ-spectrum detected on the catcher. Its half-life is considered to be of a few nanoseconds (see sect. 2). The spectrum shown in fig. 6 is a sum of prompt γ-γ coincidence spectra gated by the four strongest transitions at 351, 471, 578 and 745 keV.

ii) A second cascade of three relatively intense $E2$ transitions at 751.8, 383.2, and 679.6 keV has been placed in between a $I^\pi = 15^+$ excited state at 1.814 MeV and the $I^\pi = 9^+$ isomer (left-hand side in fig. 5). Indeed, this cascade which is also seen in the delayed γ-spectrum at the catcher appears fed from the isomeric level at 2.743 MeV via several weakly intense γ lines at 699.2, 802.0 and 1289 keV. The situation is illustrated in the upper part of fig. 7, showing the lines at 125.9 and 802.0 keV observed in coincidence. The order 751.8-383.2-679.6 retained above the 9^+ isomer is in agreement with all the γ-γ coincidence relationships.

iii) The excited level shown at 4.998 MeV in the level scheme with a tentative spin-parity assignment $I^\pi = (23,24)^+$ is established by the main cascade of four prompt γ transitions at 678.1, 636.2, 429.3 and 510.4 keV, built above the isomeric state at 2.743 MeV and displayed at the right-hand side of fig. 5. The relative position of the transitions in this cascade is based on several parallel paths: (678.1 + 636.2)/(138.9+1175.5); (636.2+429.3)/(669.6+395.4); 1348.2/(678.1+669.6). Looking at the level scheme one observes an organized group of 9 γ-rays from 268.9 to 935.6 keV which connects the $I^\pi = 15^+$ state at 1.814 MeV and the $I^\pi = (23,24)^+$ state at 4.998 MeV. This group which by-passes the isomeric state $I^\pi = (19)^+$ at 2.743 MeV is displayed at the left-hand side of fig. 5. It is relatively well fed from the excited state at 4.998 MeV ($I_\gamma(498.7)/I_\gamma(510.4) \simeq 1.5$) and receives a weak additional feeding on the $I^\pi = (20)^+$ state at 3.74 MeV. While the 498.7 keV transition is a prompt γ-ray (see table 1) all the other transitions placed below the $I^\pi = (20)^+$ excited state exhibit a slight delay (see I_γ(catcher) in table 1). These observations suggest the existence of another short-lived isomeric state feeding the 3.74 MeV excited state.

iv) Finally, a cascade of three γ-rays at 212.0, 765.5 and 166.9 keV has been observed in coincidence with all the transitions placed below 4.998 MeV in the level scheme

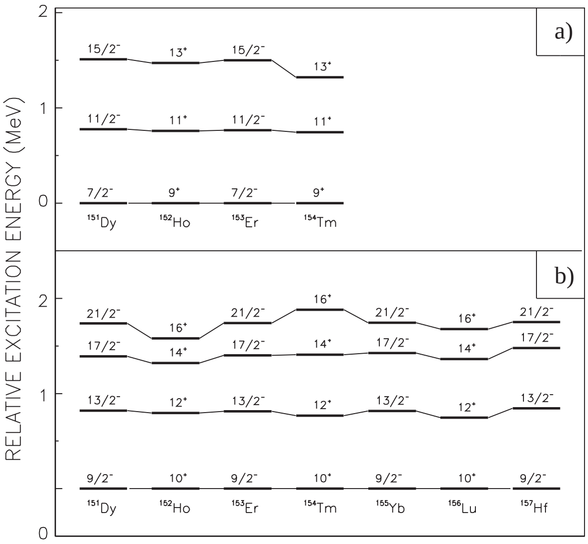

Fig. 8. Systematics of the cascades built on the $(\nu f^3_{7/2} \otimes \pi h_{11/2})_{9^+}$ states in the odd-Z, $N = 85$ isotones compared to the $(\nu f^3_{7/2})$ multiplet states in the even-Z, $N = 85$ isotones (part a), and on the $(\nu f^2_{7/2} h_{9/2} \otimes \pi h_{11/2})_{10^+}$ states in the odd-Z, $N = 85$ isotones compared to the $(\nu f^2_{7/2} h_{9/2})$ multiplet states in the even-Z, $N = 85$ isotones (part b). Results are taken from [4–8] and present work.

(fig. 5). The misassignment of lines at 167, 212, 382, 680 and 751 keV to ^{153}Tm by Kossakowski *et al.* [10] is definitively confirmed by the present data (see the example shown in the lower part of fig. 7). The three transitions of the cascade having approximatively the same intensity, their order in the cascade is only tentative. The 166.9 keV, $E1$ transition, at the top induces a parity change and a negative parity $I^\pi = (28, 29)^-$ for the highest excited state identified at 6.141 MeV in ^{154}Tm (see fig. 5).

4 Discussion

The $N = 85$ isotones of the transitional region above the $^{146}_{64}$Gd$_{82}$ core have three valence neutrons outside the $N = 82$ closed shell and a variable number of valence protons outside the $Z = 64$ closed subshell. The Fermi surface of these nuclei is located near the $\nu f_{7/2}$, $\nu h_{9/2}$ and $\pi h_{11/2}$ orbitals. For the even-Z, $N = 85$ isotones (^{151}Dy,^{153}Er) one observes two collective structures built upon the $7/2^-$ and $9/2^-$ states generated by coupling of $\nu f_{7/2}$ or $\nu h_{9/2}$ orbitals to the $\nu f^2_{7/2}$ states of the neutron cores. For the odd-Z, $N = 85$ isotones, two states close in energy, 9^+ and 10^+, can be obtained from the coupling between an unpaired $\pi h_{11/2}$ proton and a $\nu f_{7/2}$ or $\nu h_{9/2}$ neutron.

For the high-spin yrast excitations, the $\nu i_{13/2}$ orbital has to be considered as well as the couplings with the octupole vibration of the core as introduced to describe the structures observed in neighbouring nuclei [14].

Such a simple approach was successfully used to discuss the dominant yrast structure in the $N = 85$, odd-odd nucleus ^{152}Ho [5] by comparison with those identified in the $N = 85$, odd-A nuclei ^{151}Dy and ^{153}Er. In the level scheme of ^{154}Tm populated by a fusion reaction induced by ^{14}N ions, the situation differs on several points. As shown in fig. 5, the level scheme is not dominated by only one strong yrast cascade because, below 2 MeV, two parallel cascades with equivalent intensities reach the 9^+ isomeric state. The second difference is the absence of parity change along the decay chain from 6 MeV to the bottom, even if the existence of short half-lived isomers has been observed at 2.74 MeV, $I^\pi = (19)^+$ and at around 3.74 MeV. Only the 166.9 keV γ-ray placed at the top of the level scheme has been identified as an $E1$ transition.

From the $N = 85$ systematics in fig. 8 the behaviours of the two structures shown at the right-hand side of fig. 5 support $(\nu f^3_{7/2} \otimes \pi h_{11/2})_{9^+}$ and $(\nu f^2_{7/2} h_{9/2} \otimes \pi h_{11/2})_{10^+}$ configurations, respectively.

The present results exhibit important differences between ^{154}Tm and its $N = 85$ neighbours, ^{152}Ho and ^{153}Er, so it is difficult to propose realistic configurations for many excited states. However, the higher excited state $I^\pi = (28, 29)^-$ at 6.14 MeV in ^{154}Tm could correspond to the $I^\pi = 28^-$, isomeric state observed at 5.84 MeV in ^{152}Ho and interpreted by the full alignment $[(\nu f_{7/2} h_{9/2} i_{13/2})_{29/2^+} \otimes (\pi h^3_{11/2})_{27/2^-}]$ of six valence particles [5].

As for the case of ^{153}Er [6] the present partial level scheme of ^{154}Tm would be widely improved by a study using a fusion reaction induced by heavier ions.

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