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High-spin states of the semimagic nucleus $^{151}_{69}\text{Tm}_{82}$

X.H. Yu,^{1,2} M.L. Liu,^{3,4} H. Huang,^{1,2} W.Q. Zhang,^{1,2} Z. Liu,^{1,2,*} M.L. Liu,^{1,2,†} A. N. Andreyev,⁵ C.X. Yuan,³ P. M. Walker,⁶ C. Qi,⁷ J.G. Wang,^{1,2} B. Ding,^{1,2} G.J. Fu,⁸ Q.B. Zeng,^{1,2} Y.F. Wu,^{1,2} R.D. Page,⁹ B.H. Sun,¹⁰ C. Scholey,¹¹ S. Eeckhaudt,¹¹ T. Grahm,¹¹ P.T. Greenlees,¹¹ N. J. Thompson,⁶ I. G. Darby,¹² A. B. Garnsworthy,¹³ M. B. Gómez-Hornillos,¹⁴ D. G. Jenkins,⁵ P. Jones,¹⁵ R. Julin,¹⁶ D. T. Joss,⁹ S. Ketelhut,¹⁶ M. Leino,¹⁶ M. Niikura,¹⁷ M. Nyman,¹⁸ J. Pakarinen,¹⁶ S. Pietri,¹⁹ Zs. Podolyák,⁶ P. Rahkila,¹⁶ J. Sarén,¹⁶ J. Uusitalo,¹⁶ S. Williams,⁶ H.K. Wang,²⁰ and F.S. Zhang²¹

¹*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

²*University of Chinese Academy of Sciences, Beijing 100049, China*

³*Sino-French Institute of Nuclear Engineering and Technology, Sun Yat-sen University, Zhuhai 519082, China*

⁴*Center for Exotic Nuclear Studies, Institute for Basic Science, Daejeon 34126, Republic of Korea*

⁵*School of Physics, Engineering and Technology,*

University of York, York, YO10 5DD, United Kingdom

⁶*Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom*

⁷*KTH, Alba Nova University Center, SE-10691 Stockholm, Sweden*

⁸*School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*

⁹*Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK*

¹⁰*School of Physics, Beihang University, Beijing 100191, China*

¹¹*University of Jyväskylä, Department of Physics,*

P.O. Box 35, FI-40014 University of Jyväskylä, Finland

¹²*SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8GG, UK*

¹³*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*

¹⁴*STFC, Daresbury Laboratory, Daresbury, Warrington, WA4 4AD, United Kingdom*

¹⁵*Themba LABS, National Research Foundation, PO Box 722, Somerset West, South Africa*

¹⁶*Accelerator Laboratory, Department of Physics,*

University of Jyväskylä, FI-40014 Jyväskylä, Finland

¹⁷*CNS, University of Tokyo, Tokyo 351-0100, Japan*

¹⁸*Department of Physics, University of Helsinki, FI-00014 Helsinki, Finland*

¹⁹*GSI Helmholtzzentrum für Schwerionenforschung, D-64291 Darmstadt, Germany*

²⁰*Zhejiang Key Laboratory of Quantum State Control and Optical Field Manipulation, Department of Physics, Zhejiang Sci-Tech University, 310018 Hangzhou, China*

²¹*The Key Laboratory of Beam Technology of Ministry of Education,*

College of Nuclear Science and Technology, Beijing Normal University, Beijing 100875, China

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High-spin states of the semimagic nucleus $^{151}_{69}\text{Tm}_{82}$ have been studied in the $^{96}\text{Ru}(^{58}\text{Ni}, 3p)$ reaction. The level scheme is considerably extended up to 12 MeV in excitation energy. More than 50 new γ -ray transitions and 40 new levels are identified. The Configuration Interaction Shell Model (CISM) calculations were performed in the full proton model space and compared with experimental results. Four new sequences above the fully aligned $[\pi(h_{11/2})^5]_{35/2^-}$ state are established, including proton excitations across the $Z = 64$ subshell and possible neutron excitations across the $N = 82$ shell gap.

I. INTRODUCTION

Shell effects play a central role in shaping our understanding of nuclear structure. Studies of the shell effects provide key tests for proton and neutron shell gaps, clarify single-particle configurations, and improve the reliability of nuclear effective interactions. One of interesting regions for such studies, both experimentally and theoretically, is around the proton subshell at $Z = 64$ [1] and the neutron closed shell at $N = 82$ [1, 2].

Near $^{146}_{64}\text{Gd}_{82}$, the proton orbitals $g_{7/2}$ and $d_{5/2}$ constitute the $Z = 64$ subshell closure [3], lying below

the higher $0h_{11/2}$, $2s_{1/2}$ and $1d_{3/2}$ orbitals [4]. Of particular importance is the high- j orbital $0h_{11/2}$, which serves an important purpose in the yrast states of such nuclei. Indeed, the $\pi h_{11/2}^n$ configurations were found to dominate high-spin levels up to the fully aligned states at 10^+ , $27/2^-$, 16^+ and $35/2^-$ in ^{148}Dy , ^{149}Ho , ^{150}Er and ^{151}Tm [5–8] with $n = 2, 3, 4$ and 5 , respectively.

As the angular momenta becomes exhausted in the proton valence space, in higher-spin and higher-energy states, particle-hole (p - h) excitations across the $Z = 64$ proton subshell and/or the $N = 82$ neutron shell closure will set in and compete. Since the neutron shell gap (~ 4 MeV) is significantly larger than the proton subshell gap (~ 2 MeV) [1, 2], one expects that neutron cross-shell excitations will take place at higher excitation energy than the proton ones. Indeed, such competing excitations

* liuzhong@impcas.ac.cn

† liuml@impcas.ac.cn

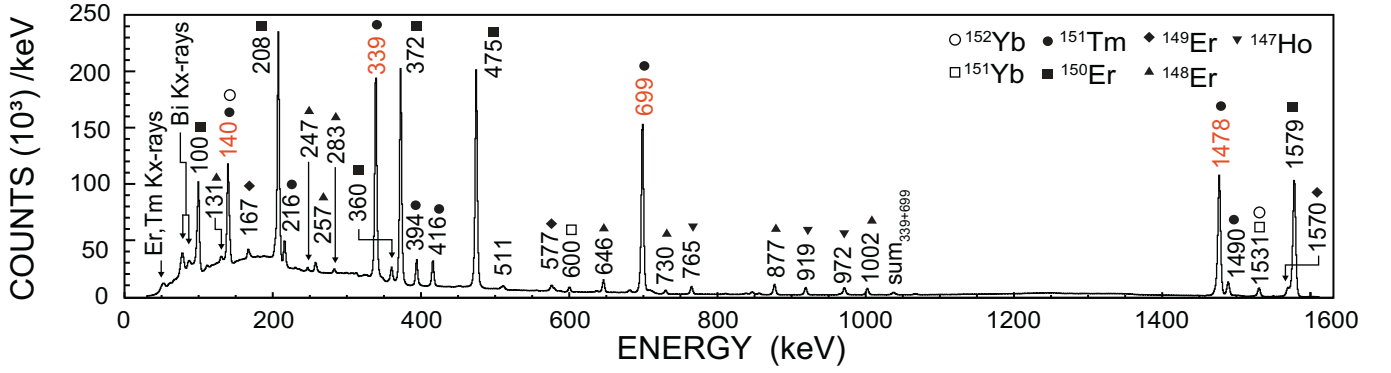


FIG. 1: The background-subtracted delayed γ -ray spectrum for clovers in GREAT spectrometer within $2 \mu\text{s}$ after the ERs implantation. The prominent γ rays originating from the known microsecond isomers in ^{147}Ho , $^{148-150}\text{Er}$, ^{151}Tm , and $^{151-152}\text{Yb}$ are labeled. The four strongest γ rays at 140-, 339-, 699- and 1478-keV from the known $(27/2^-)$ isomer in ^{151}Tm [8–10] are highlighted in red. A background spectrum from the time interval $2 < \Delta T(ER - \gamma) < 4 \mu\text{s}$ has been subtracted.

have been identified in the $N = 82$ isotones $^{133}_{51}\text{Sb}$ [11], $^{134}_{52}\text{Te}$, $^{135}_{53}\text{I}$ [12], $^{136}_{54}\text{Xe}$, $^{137}_{55}\text{Cs}$, $^{138}_{56}\text{Ba}$ [13] and tentatively assigned in $^{139}_{57}\text{La}$ [13], $^{141}_{59}\text{Pr}$ [14].

In this work, we present new results obtained on high-spin states of the semimagic nucleus $^{151}_{69}\text{Tm}_{82}$ produced via the $^{96}\text{Ru}(^{58}\text{Ni}, 3p)$ fusion evaporation reaction. Its high-spin states were investigated using a selective recoil isomer tagging (**RIT**) method [15] together with the prompt γ - γ coincidence technique. The experimental details are introduced in Sec. II, while the experimental results are presented in Sec. III. In Sec. IV, the level structures are discussed on the basis of experimental systematics in $N = 82$ isotones and compared with the **CISM** calculations, and a summary is given in Sec. V.

II. EXPERIMENTAL DETAILS

The experiment was carried out using the gas-filled recoil separator RITU at the University of Jyväskylä. High spin states of ^{151}Tm were populated in the $^{96}\text{Ru}(^{58}\text{Ni}, 3p)$ reaction. The ^{58}Ni beam was provided by the K130 cyclotron, to bombard a self-supporting, $500 \mu\text{g}/\text{cm}^2$ ^{96}Ru target with an isotopic enrichment of $\sim 95\%$ at energies of 266 MeV and 274 MeV. The beam was delivered with an average current of 3 particle nA for 110 hours.

Prompt γ rays produced in the fusion-evaporation reactions were detected by the JUROGAM array [16], consisting of 43 Compton-suppressed single crystal Ge detectors around the target chamber. They were positioned at angles of 72.05° , 85.84° , 94.16° , 107.94° , 133.57° and 157.6° to the beam direction. The energy and efficiency calibrations in the range of 0-2000 keV were performed using ^{152}Eu and ^{133}Ba standard sources. Typical energy resolutions were about 3.0–3.4 keV for full width at half maximum (FWHM) for the 1408-keV

line. The in-beam data was then sorted into coincidence γ - γ matrices and a γ - γ - γ cube, and analyzed using the RADWARE [17] and CERN ROOT [18]. In total, about 3×10^8 γ - γ - γ coincidence events were obtained.

After a time of flight of approximately 0.5 μs through the RITU separator, the evaporation residues (ERs) and following decays were detected by the GREAT spectrometer at focal plane [19]. The ERs passed through a gas-filled multiwire proportional chamber (MWPC) and were then implanted into two 300- μm thick, 40 mm $\times$ 60 mm double-sided silicon strip detectors (DSSSDs). A planar Ge detector was mounted behind the DSSSDs, which were surrounded by 3 Ge-clover Ge detectors. These detectors recorded the recoil implantation, subsequent proton, α -, β - decays, conversion electrons, X-rays, and γ -rays.

III. MEASUREMENTS AND RESULTS

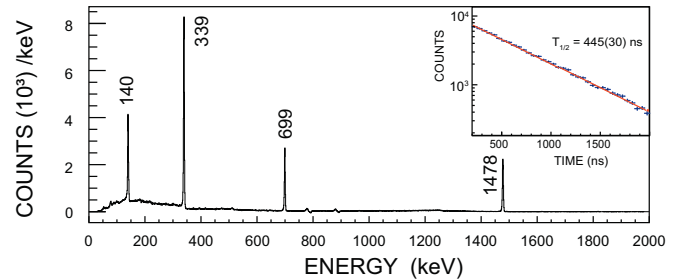


FIG. 2: The background-subtracted delayed gamma spectrum from γ - γ coincidences in ^{151}Tm . The γ rays were gated by the 699- or 1478-keV γ -rays detected in the Ge-clover detectors of the GREAT spectrometer. The inset is the corresponding time distribution of $\Delta T[ER - \gamma(699, 1478)]$.

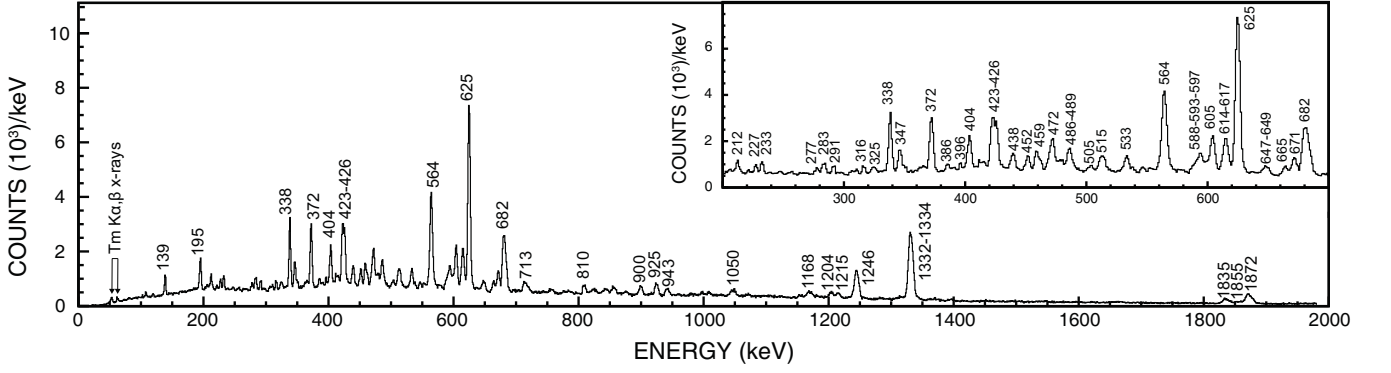


FIG. 3: The background-subtracted RIT spectrum of ^{151}Tm measured by the JUROGAM detectors, with the gates on delayed γ -ray transitions ($0 < \Delta T[ER - \gamma(699, 1478)] < 2 \mu\text{s}$) following the $0.445 \mu\text{s}$ isomer and detected by Ge-clover detectors of GREAT. The majority of gamma peaks are new for ^{151}Tm . The background spectrum is subtracted by gates on the nearby Compton background and the $2 < \Delta T[ER - \gamma(699, 1478)] < 4 \mu\text{s}$ interval. The inset is the zoom from 200 to 700 keV.

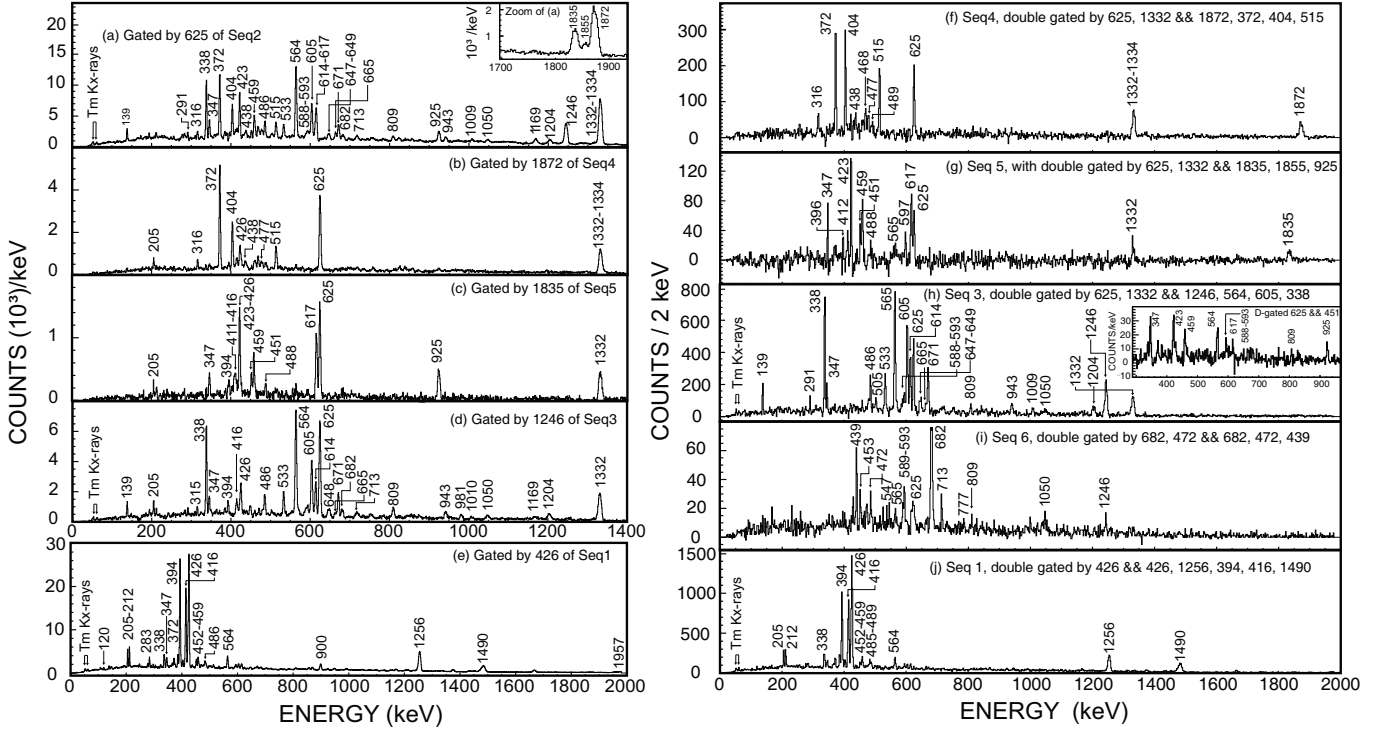


FIG. 4: Single-gated spectra from γ - γ coincidences (a)-(e) and double-gated spectra from γ - γ - γ coincidences (f)-(j) measured with JUROGAM only, most of peaks are new transitions for ^{151}Tm . Their gating conditions are shown and the background was subtracted by gating on Compton background near the gating peak.

A. Levels below the $(27/2^-)$ isomer in ^{151}Tm

The background-subtracted spectrum of delayed γ rays within $2 \mu\text{s}$ after implantation is presented in Fig. 1, where the most intense γ peaks are known transitions from ^{151}Tm and ^{150}Er [7, 10].

Figure. 2 shows the spectrum of delayed γ rays in ^{151}Tm in coincidence with the 699- or 1478-keV transitions in the time interval of

$\Delta T[ER - \gamma(699, 1478)] = 0 - 2 \mu\text{s}$. Background spectra with the condition of $\Delta T[ER - \gamma(699, 1478)] = 2 - 4 \mu\text{s}$ and with a gate on the Compton background adjacent to the gating peak have been subtracted. This helps to reduce the γ rays from long-lived isomers, such as the 140-keV transition from the $30\text{-}\mu\text{s}$ isomer in ^{152}Yb [20]. Fig. 2 confirms that the known isomeric γ rays of 140-, 339-, 699- and 1478-keV are in coincidence. The time distribution $\Delta T[ER - \gamma(699, 1478)]$ is presented in the

inset of Fig. 2. The half-life of the isomer was measured as 445(30) ns, in good agreement with the literature value of 466(34) ns [10].

B. High spin states above the $(27/2^-)$ isomer

RIT analysis. To investigate high-spin states in ^{151}Tm , we used the RIT technique. Figure 3 shows the background-subtracted spectrum measured with JUROGAM tagged with delayed γ -ray transitions ($0 < \Delta T(ER - \gamma(699, 1478)) < 2 \mu\text{s}$) de-exciting the $(27/2^-)$ isomer detected by the GREAT clovers detectors. More than 50 new γ -ray transitions of ^{151}Tm were observed, albeit with reduced statistics due to the in-flight decay losses inside the RITU separator.

In-beam analysis. The new transitions observed using RIT were further confirmed in the γ - γ and γ - γ - γ coincidence analysis of prompt in-beam data collected by JUROGAM. Representative coincidence spectra are shown in Fig. 4 and the established level scheme is given in Fig. 5. The experimental results for these γ -ray transitions are listed in Table I. Six level sequences labeled as Seq.1-6, were established with Seq.3-6 being new. New levels are established based on relative intensities of γ -ray transitions and their possible multiplicities.

Sequences 1 and 2 were previously reported in Ref. [8–10] and are confirmed in this work as shown in Figs. 4(a,e,j).

Sequence 3 has the highest intensity at high spins in ^{151}Tm , and it is established on top of the known 1246-keV transition, which feeds the 4613-keV level of Seq.2. Representative coincidence spectra for Seq.3 are shown in Figs. 4(d,h).

Three new transitions at 1872-, 1855-, 1835-keV can be seen in the 625-keV gated spectrum in the inset of Fig. 4(a), but they are not in mutual coincidence as shown in Figs. 4(b,c,f,g).

Based on the γ - γ and γ - γ - γ coincidences analysis for these transitions in Figs. 4(b,c,f,g), two new sequences labeled as Seq.4 and Seq.5, are established. As illustrated in the inset of Fig. 4(h), the 9323-keV level in Seq.3 also decays by the 451-keV interband transition to the 8872-keV level in Seq.5.

Sequence 6, consisting of the 682-, 682-, 472-, 713- and 547-keV transitions, is tentatively built above the known 24-ns isomer at 6909-keV [10]. Since the velocity of ER is approximately 1 cm/ns (~ 500 ns flight in RITU separator), the γ - γ coincidences between transitions above and below the 24-ns isomer are not efficiently detected by the JUROGAM array (the 1050-keV transition is shown in dashed arrow in Fig. 5). This gives rise to only partial intensities for transitions of Seq.6 in the coincidence spectrum with the gate of 625 keV in Fig. 4(a), but full intensities for the transitions above the 24-ns isomer in the RIT spectrum (e.g. 682-keV transitions in Fig. 3).

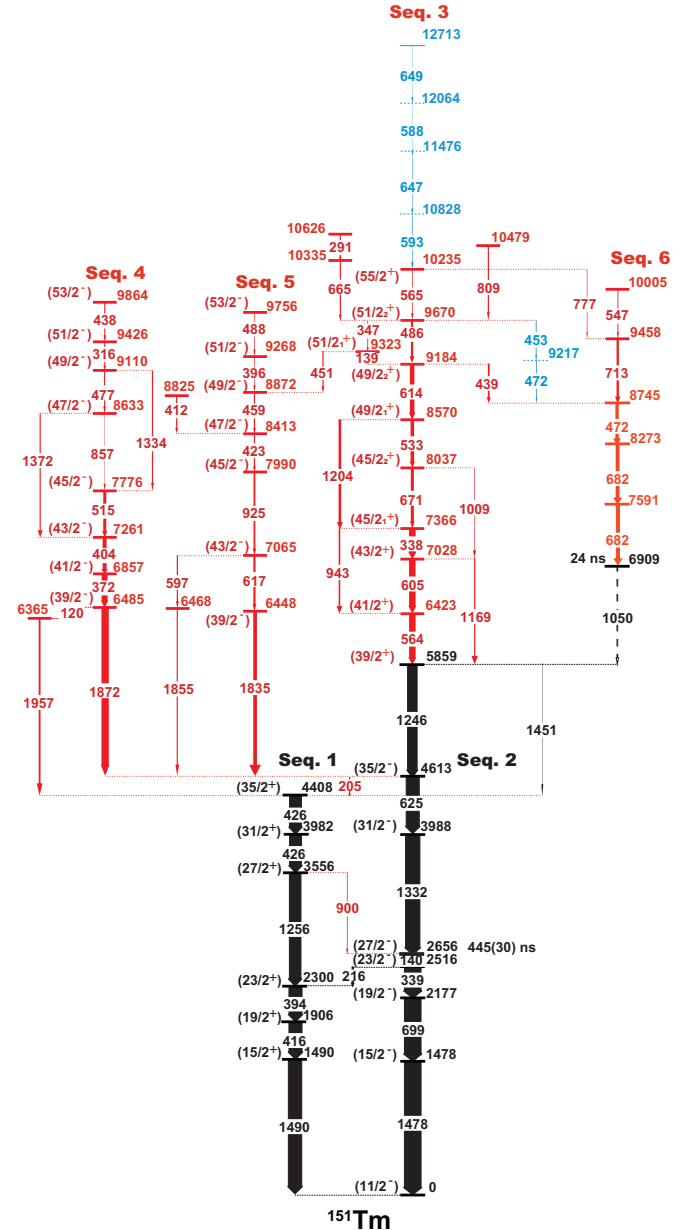


FIG. 5: The level scheme of ^{151}Tm . New transitions established in this work are shown in red or blue. The order of γ rays shown in blue cannot be determined unambiguously because of their low statistics or close energies.

C. Angular distributions and correlations

To investigate the multiplicities of prompt γ -ray transitions, their angular distributions (AD) and angular correlations (AC) were measured in this work. The angular distribution for the transitions [22] were extracted with RIT conditions and the representative distributions are shown in Fig. 6.

TABLE I: γ -ray energies E_γ , relative intensities I_γ , initial and final level energies $E_i \rightarrow E_f$, angular correlation (anisotropy) ratios R_{AC} , angular distribution ratios R_{AD} and multipolarities assignments of the transitions in ^{151}Tm . The 625- and 1332-keV transitions of Seq.2 are labelled in bold since they are the reference values for $R_{AC,AD}$.

$E_\gamma(\text{keV})^*$	$I_\gamma^\&$	$I_i^\pi \rightarrow I_f^\pi$	$E_i \rightarrow E_f$	R_{AC}	R_{AD}	$ML^\#$
Seq.1						
1490	83.2(4.2)	$(15/2^+) \rightarrow (11/2^-)$	$1490 \rightarrow 0$	1.20(0.09)		(M2/E3)
416	84.4(4.2)	$(19/2^+) \rightarrow (15/2^+)$	$1906 \rightarrow 1490$	1.11(0.08)		(E2)
394	86.0(5.2)	$(23/2^+) \rightarrow (19/2^+)$	$2300 \rightarrow 1906$	1.06(0.07)		(E2)
1256	86.1(9.5)	$(27/2^+) \rightarrow (23/2^+)$	$3556 \rightarrow 2300$	1.22(0.10)		(E2)
426	92.7(6.8)	$(31/2^+) \rightarrow (27/2^+)$	$3982 \rightarrow 3556$	1.17(0.09)		(E2)
426	92.7(6.8)	$(35/2^+) \rightarrow (31/2^+)$	$4408 \rightarrow 3982$	1.17(0.09)		(E2)
205	6.5(0.6)	$(35/2^+) \rightarrow (35/2^-)$	$4613 \rightarrow 4408$	0.68(0.25)		(E1)
900	8.2(0.9)	$(27/2^+) \rightarrow (27/2^-)$	$3556 \rightarrow 2656$	0.87(0.18)		(E1)
216 [@]		$(23/2^-) \rightarrow (23/2^+)$	$2516 \rightarrow 2300$			(E1)
Seq.2						
1478 [@]		$(15/2^-) \rightarrow (11/2^-)$	$1478 \rightarrow 0$			(E2)
699 [@]		$(19/2^-) \rightarrow (15/2^-)$	$2177 \rightarrow 1478$			(E2)
339 [@]		$(23/2^-) \rightarrow (19/2^-)$	$2516 \rightarrow 2177$			(E2)
140 [@]		$(27/2^-) \rightarrow (23/2^-)$	$2656 \rightarrow 2516$			E2
1332	96.4(8.2)	$(31/2^-) \rightarrow (27/2^-)$	$3988 \rightarrow 2656$	1.31(0.10)		(E2)
625	100.0(5.4)	$(35/2^-) \rightarrow (31/2^-)$	$4613 \rightarrow 3988$	1.28(0.12)	1.13(0.11)	(E2)
Seq.3						
1246	46.8(2.5)	$(39/2^+) \rightarrow (35/2^-)$	$5859 \rightarrow 4613$	1.18(0.12)	1.17(0.24)	(M2/E3)
564	39.5(7.6)	$(41/2^+) \rightarrow (39/2^+)$	$6423 \rightarrow 5859$	0.92(0.18)		(M1/E2)
605	34.3(1.9)	$(43/2^+) \rightarrow (41/2^+)$	$7028 \rightarrow 6423$	0.67(0.08)	0.87(0.17)	(M1/E2)
338	29.0(1.5)	$(45/2_1^+) \rightarrow (43/2^+)$	$7366 \rightarrow 7028$	0.87(0.09)	0.76(0.13)	(M1/E2)
671	13.4(1.3)	$(45/2_2^+) \rightarrow (45/2_1^+)$	$8037 \rightarrow 7366$	1.25(0.23)		(E2)
533	9.2(1.0)	$(49/2_1^+) \rightarrow (45/2_2^+)$	$8570 \rightarrow 8037$	1.49(0.24)		(E2)
614	16.1(1.0)	$(49/2_2^+) \rightarrow (49/2_1^+)$	$9184 \rightarrow 8570$	1.41(0.21)		(E2)
139	6.5(0.4)	$(51/2_1^+) \rightarrow (49/2_2^+)$	$9323 \rightarrow 9184$	0.67(0.25)	0.55(0.18)	(M1/E2)
347	9.7(1.3)	$(51/2_2^+) \rightarrow (51/2_1^+)$	$9670 \rightarrow 9323$	1.36(0.18)		(E2)
486	10.6(1.8)	$(51/2_2^+) \rightarrow (49/2_2^+)$	$9670 \rightarrow 9184$	0.82(0.13)		(M1/E2)
565	11.5(7.6)	$(55/2^+) \rightarrow (51/2_2^+)$	$10235 \rightarrow 9670$	1.28(0.18)		(E2)
593	< 4		$10828 \rightarrow 10235$			
647	< 2		$11475 \rightarrow 10828$			
588	< 2		$12063 \rightarrow 11475$			
649	< 2		$12712 \rightarrow 12063$			
809	< 4		$10479 \rightarrow 9670$			
1169	6.6(0.5)	$(43/2^+) \rightarrow (39/2^+)$	$7028 \rightarrow 5859$	1.42(0.19)		(E2)
943	5.1(0.6)	$(45/2_1^+) \rightarrow (41/2^+)$	$7366 \rightarrow 6423$	1.45(0.16)		(E2)
1010	3.3(0.8)	$(45/2_2^+) \rightarrow (43/2^+)$	$8037 \rightarrow 7028$	0.61(0.31)		(M1/E2)
1204	10.2(0.6)	$(49/2_1^+) \rightarrow (45/2_1^+)$	$8570 \rightarrow 7366$	1.72(0.24)		(E2)
Seq.4						
1872	34.5(3.5)	$(39/2^-) \rightarrow (35/2^-)$	$6485 \rightarrow 4613$	1.51(0.11)	1.64(0.13)	(E2)
372	28.4(1.6)	$(41/2^-) \rightarrow (39/2^-)$	$6857 \rightarrow 6485$	0.65(0.07)	0.64(0.06)	(M1/E2)
404	18.2(1.1)	$(43/2^-) \rightarrow (41/2^-)$	$7261 \rightarrow 6857$	0.61(0.12)	0.67(0.09)	(M1/E2)
515	9.1(1.0)	$(45/2^-) \rightarrow (43/2^-)$	$7776 \rightarrow 7261$	0.51(0.12)		(M1/E2)
857	< 2	$(47/2^-) \rightarrow (45/2^-)$	$8633 \rightarrow 7776$			(M1/E2)
1372	3.7(0.8)	$(47/2^-) \rightarrow (43/2^-)$	$8633 \rightarrow 7261$	1.34(0.31)		(E2)
1334	4.6(1.4)	$(49/2^-) \rightarrow (45/2^-)$	$9110 \rightarrow 7776$			(E2)
477	5.9(1.0)	$(49/2^-) \rightarrow (47/2^-)$	$9110 \rightarrow 8632$	0.61(0.24)		(M1/E2)
316	5.5(0.5)	$(51/2^-) \rightarrow (49/2^-)$	$9426 \rightarrow 9110$	0.57(0.19)		(M1/E2)
438	3.6(0.7)	$(53/2^-) \rightarrow (51/2^-)$	$9864 \rightarrow 9426$	0.62(0.21)		(M1/E2)

TABLE I: (Continued.)

$E_\gamma(\text{keV})^*$	$I_\gamma^{\&}$	$I_i^\pi \rightarrow I_f^\pi$	$E_i \rightarrow E_f$	R_{AC}	R_{AD}	$ML^\#$
1957	< 2		6365 $\rightarrow$ 4408			
120	< 2		6485 $\rightarrow$ 6365			
Seq.5						
1835	12.3(3.5)	(39/2 ⁻) $\rightarrow$ (35/2 ⁻)	6448 $\rightarrow$ 4613	1.47(0.20)	1.44(0.35)	(E2)
1855	4.8 (2.2)		6468 $\rightarrow$ 4613			
617	10.3(0.8)	(43/2 ⁻) $\rightarrow$ (39/2 ⁻)	7065 $\rightarrow$ 6448	1.26(0.22)		(E2)
597	3.6(1.1)		7065 $\rightarrow$ 6468			
925	11.3(0.7)	(45/2 ⁻) $\rightarrow$ (43/2 ⁻)	7990 $\rightarrow$ 7065	0.60(0.19)	0.75(0.24)	(M1/E2)
423	9.7(1.2)	(47/2 ⁻) $\rightarrow$ (45/2 ⁻)	8413 $\rightarrow$ 7990	0.48(0.07)		(M1/E2)
459	7.2(0.4)	(49/2 ⁻) $\rightarrow$ (47/2 ⁻)	8872 $\rightarrow$ 8413	0.73(0.24)		(M1/E2)
396	2.9(0.2)	(51/2 ⁻) $\rightarrow$ (49/2 ⁻)	9268 $\rightarrow$ 8872	0.68(0.16)		(M1/E2)
488	2.1(0.3)	(53/2 ⁻) $\rightarrow$ (51/2 ⁻)	9756 $\rightarrow$ 9268	0.71(0.20)		(M1/E2)
451	5.1(0.3)	(51/2 ⁺) $\rightarrow$ (49/2 ⁻)	9323 $\rightarrow$ 8872	0.79(0.26)		(E1)
Seq.6[§]						
1050			6909 $\rightarrow$ 5859			
682	20.3(4.0)		7591 $\rightarrow$ 6909			
682	20.3(4.0)		8273 $\rightarrow$ 7591			
472	11.8(3.1)		8745 $\rightarrow$ 8273			
713	3.4(0.3)		9458 $\rightarrow$ 8745			
547	< 2		10005 $\rightarrow$ 9458			
472	< 2		9217 $\rightarrow$ 8745			
453	< 2		9670 $\rightarrow$ 9217			
439	5.2(1.4)		9184 $\rightarrow$ 8745			
777	< 2		10235 $\rightarrow$ 9458			

* Due to the Doppler shift and Doppler broadening of in-beam γ peaks [21], the resolution for γ -ray energies is adopted as 1 keV.

& The relative intensities are normalized to the known 625-keV transition of Seq.2 with $I_\gamma = 100.0$.

Multipolarity assignments are based on $R_{AD,AC}$ values in Section III.C and the theoretical interpretation in Section IV.

@ The delayed γ rays below the (27/2⁻) isomer. Their intensities are not compared with those of prompt γ rays in the table.

§ Seq.6 is built above the known 24-ns isomer, see the text.

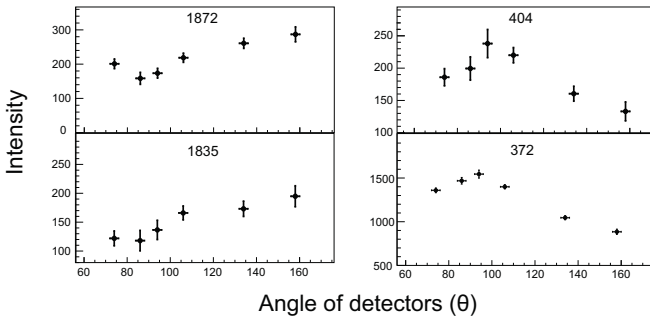


FIG. 6: Representative angular distributions for γ -ray transitions extracted from RIT. The γ -ray energies in keV are given in each panel.

The angular distribution ratio was defined as:

$$R_{AD} = \frac{I_\gamma(133.57^\circ \text{ or } 157.6^\circ)}{I_\gamma(85.84^\circ \text{ or } 94.16^\circ)} \quad (1)$$

where intensities of the γ rays (I_γ) are obtained with isomer tagging, sorted into small angles (133.57° and 157.6°) and large angles (85.84° and 94.16°), and normalized by the respective efficiencies of the two sets of detectors.

Based on the strong transitions with known multiplicities in ^{148}Er [23], ^{150}Er [7] and ^{151}Tm [10], typical R_{AD} values for dipole and stretched quadrupole transitions in this work are found to be ~ 0.7 and ~ 1.24 , respectively. They are used as reference values for other γ rays (i.e. the dashed line in Fig. 7).

We note that, due to the unresolved peaks (e.g 614- and 617-keV) or low intensities (e.g. transitions in Seq.1) in the RIT spectrum, it is impractical to extract R_{AD} values for such transitions.

Therefore, an alternative method of two-point angular correlation (anisotropy) ratios [24], denoted as R_{AC} , was

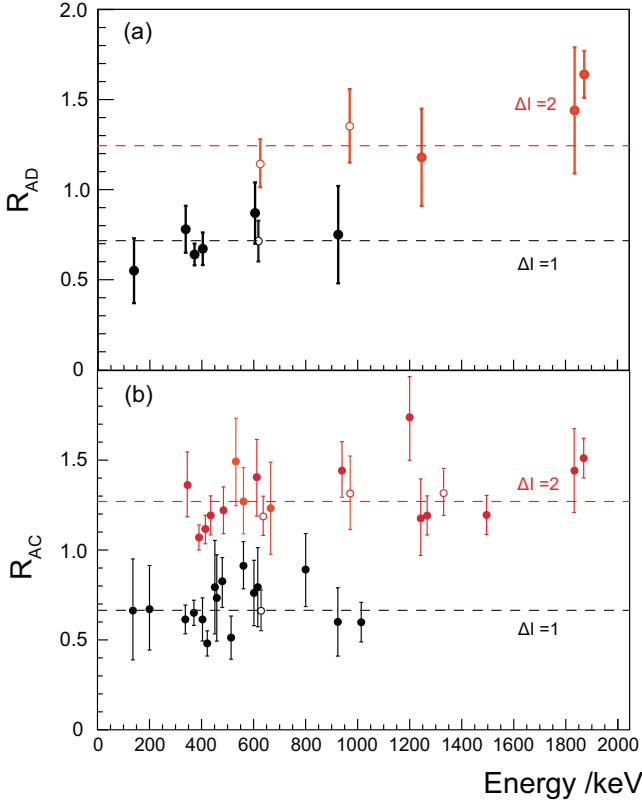


FIG. 7: R_{AD} and R_{AC} ratios deduced in this work. Reference values are shown by open circles and horizontal dashed lines.

used.

$$R_{AC} = \frac{I_{\gamma}(\text{at } 133.57^{\circ} \text{ or } 157.6^{\circ}, \text{gated on all angles})}{I_{\gamma}(\text{at } 85.84^{\circ} \text{ or } 94.16^{\circ}, \text{gated on all angles})} \quad (2)$$

where the I_{γ} values were extracted from two asymmetric γ - γ coincident matrices, with γ rays measured by Ge detectors at 133.57° or 157.6° and 85.84° or 94.16° on one axis and all detectors on the other.

Typical R_{AC} values for known dipole and stretched quadrupole transitions were ~ 0.7 and ~ 1.28 in this work. The corresponding results are shown in Table I and Fig. 7. While the $R_{AD,AC}$ values for quadrupole transitions were unique, they were not distinguishable for E1 and M1/E2 transitions. Therefore, the multipolarity assignments will be guided by the theoretical interpretation in Section IV.

IV. SHELL-MODEL CALCULATIONS AND DISCUSSION

To interpret the level structure of $^{151}_{69}\text{Tm}_{82}$, Configuration Interaction Shell-Model (CISM) calculations [25, 26] were performed. As shown in Fig. 8, we considered five proton orbitals between $Z = 50$ and 82, collectively denoted as *gdsh*

($0g_{7/2}, 1d_{5/2}, 0h_{11/2}, 2s_{1/2}, 1d_{3/2}$). Due to the limitations of computation capability, the number of protons allowed to excite across the $Z = 64$ subshell was restricted to four (denoted as $\pi(p-h)$). The neutron model space was limited to neutron orbitals below $N = 82$ (i.e. without neutron excitation across $N = 82$ shell gap).

In the present work, the effective Hamiltonian [26] was constructed using the monopole-based universal interaction V_{MU} [27] together with the M3Y-type spin-orbit interaction [28] ($V_{\text{MU}} + \text{LS}$). To reflect the experimentally observed changes in the SPEs in the range of $Z = 50-70$, the SPEs of the corresponding orbitals were lowered: by 300 keV for protons in the $0h_{11/2}$, $2s_{1/2}$, $1d_{3/2}$ orbitals. The present calculations were performed with the code KSHELL [29]. The comparison of the experimental levels and calculated excitation energies is presented in Section A, while orbital occupancy numbers are listed in Tables II and III.

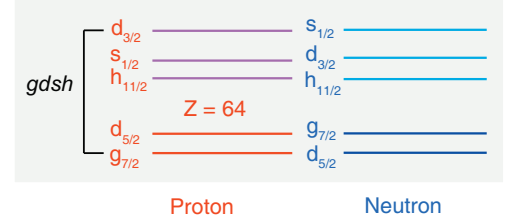


FIG. 8: Schematic diagram of single-particle orbits for protons and neutrons.

A. Proton excitations

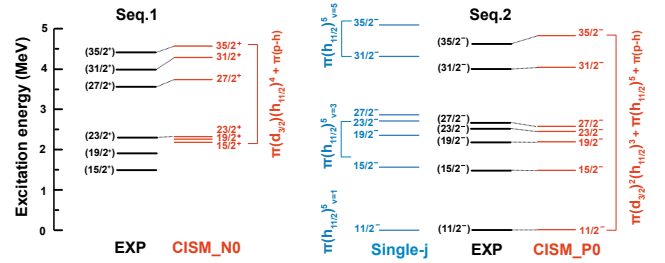


FIG. 9: Comparison between experimental level energies of Seq.1-2 and theoretical calculations for low-lying states. The CISM calculations are marked in red and their occupancy numbers are listed in Table II. The calculations of single- j shell model are from Ref. [30] and marked in blue.

SEQS.1-2 In Seq.2, the level sequence from $(11/2^-)_{g.s.}$ to $(35/2^-)$ exhibits a typical seniority pattern of the valence proton $\pi(h_{11/2})^5$ configuration [30, 31]. These states can be described by a seniority quantum number $\nu = 1, 3, 5$, which represents the number of unpaired protons in the single- j orbital $0h_{11/2}$. This

TABLE II: The two strongest components of wave functions and their partitions for the low-lying levels in CISM.

J^π	protons per orbital					Partitions (%)
	$0g_{7/2}$	$1d_{5/2}$	$1d_{3/2}$	$2s_{1/2}$	$0h_{11/2}$	
CISM_P0						
$15/2^+$	8	6	1	0	4	31
	8	4	1	0	6	9
$19/2^+$	8	6	1	0	4	29
	8	4	1	0	6	8
$23/2^+$	8	6	1	0	4	34
	8	4	1	0	6	10
$27/2^+$	8	6	1	0	4	50
	8	4	1	0	6	11
$31/2^+$	8	6	1	0	4	55
	8	4	1	0	6	10
$35/2^+$	8	6	1	0	4	60
	8	4	1	0	6	10
CISM_N0						
$11/2^-$	8	6	2	0	3	17
	8	6	0	0	5	13
$15/2^-$	8	6	2	0	3	18
	8	6	0	0	5	14
$19/2^-$	8	6	0	0	5	19
	8	6	2	0	3	19
$23/2^-$	8	6	0	0	5	21
	8	6	2	0	3	20
$27/2^-$	8	6	0	0	5	21
	8	6	2	0	3	19
$31/2^-$	8	6	2	0	3	20
	8	6	0	0	5	17
$35/2^-$	8	6	0	0	5	40
	8	4	2	0	5	20

seniority pattern of Seq.2 was well reproduced in the low-lying states of ^{150}Er , ^{151}Tm and ^{152}Yb [30]. As shown in Fig. 9, the single- j shell model calculations are compared with the experimental levels of Seq.2 within 500-keV deviation. By considering the mixing components of pair scattering and proton $p-h$ excitations across the $Z=64$ subshell, the differences between the experimental results and CISM calculations are under 200 keV.

In Seq.1, the positive-parity level sequence from (15/2⁺) to (35/2⁺) have $\pi d_{3/2} \otimes \pi[(h_{11/2})^4_{\nu=2,4}]_{6+,8+,10+,12+,14+,16+}$ configurations. As shown in Fig. 9, the CISM calculations are roughly 100-300 keV higher than the observed levels from (23/2⁺) to (35/2⁺), but showed significant deviation (~ 0.7 MeV) for the (15/2⁺) state due to the collective octupole nature of the 3⁻ core state in ^{150}Er [7]. The transitions from 15/2⁺ to 11/2⁻ were also found in ^{147}Tb , ^{149}Ho and ^{151}Tm [6, 10, 32]. It is well known that such collective octupole excitations are beyond the scope of shell model description. Based on the empirical shell-model description of $[\pi h_{11/2} \otimes s_{1/2}]_{5-}$ level in ^{150}Er [7], the considerable energy shift (~ 0.4 MeV) for the (19/2⁺) state in CISM can be explained as the possible configuration mixing with $\pi s_{1/2} \otimes \pi[(h_{11/2})^4_{\nu=2}]_{10+}$.

SEQ.3 Since 35/2⁻ is the fully aligned state of the $[\pi(h_{11/2})^5]$ configuration, the states above it in Seq.3 probably involve $p-h$ excitations of the $^{146}\text{Gd}_{82}$ core. In the $A \sim 150$ region, the $Z=64$ proton subshell gap is approximately 2 MeV [1], while the $N=82$ neutron shell gap is close to 4 MeV [2]. Therefore, high-spin states involving the proton excitation across the $Z=64$ subshell closure is expected to remain yrast immediately above the $[\pi(h_{11/2})^5]_{35/2-}$ state.

The first state in Seq.3 at 5859 keV may be of this type. It was assigned as (37/2) in the previous research. [10] We change the spin of 5859-keV level from 37/2 to 39/2 because of the present measured ADO ratio of the 1246-keV transition showing to be quadrupole in character. According to the systematics presented in Fig. 10, it can be assigned as the fully aligned five-quasiparticle (5qp) $[\pi(h^4_{11/2}g_{7/2}^{-1})]_{39/2+}$ state. The corresponding 4qp state with the configuration $\pi(h^3_{11/2}g_{7/2}^{-1})$ is known in ^{146}Gd (7165 keV), ^{148}Dy (6265 keV) [7] and newly established in ^{150}Er (6155 keV) [33].

As shown in Fig. 10, the energy differences between the 4 and 2 qp states are ~ 3300 keV in the neighboring even mass $N=82$ isotones. This energy difference can be regarded as one proton excite from $g_{7/2}$ to $h_{11/2}$ orbital. The systematics will remain robust since the $Z=64$ subshell and the pairing gap are stable in these isotones. For the assumed 5qp state $\pi(h^4_{11/2}g_{7/2}^{-1})_{39/2+}$ state at 5859 keV in ^{151}Tm , it can be originated from the coupling of the 17⁻ state in ^{150}Er with a proton in $h_{11/2}$ orbital considering the Pauli principle. The corresponding energy difference between the 5 and 3 qp states is 3203 keV, which follows the systematics and supports the above configuration assignment for the (39/2⁺) state. The 1246-keV linking transition to the (35/2⁻) state of Seq.2 will have an M2 character, which is also consistent with its $R_{AC,AD}$ values of ~ 1.2 ($\Delta I=2$) in Table I.

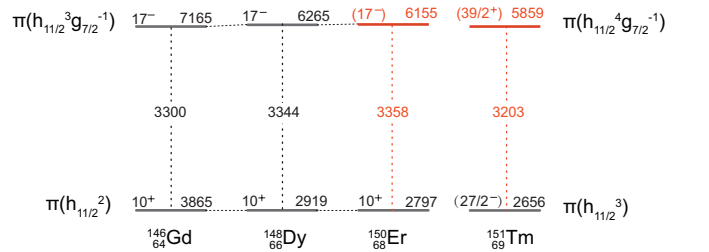


FIG. 10: Systematics of energy differences between the fully aligned 4qp $[\pi(h^3_{11/2}g_{7/2}^{-1})]_{17-}$ and 2qp $[\pi(h^2_{11/2})]_{10+}$ states in ^{146}Gd , ^{148}Dy and ^{150}Er , as well as the 5qp $[\pi(h^4_{11/2}g_{7/2}^{-1})]_{39/2+}$ and 3qp $[\pi(h^3_{11/2})]_{27/2-}$ states in ^{151}Tm . The corresponding 5qp states in ^{147}Tb and ^{149}Ho are not identified, while the (17⁻) state in ^{150}Er [33] and (39/2⁺) state in ^{151}Tm were assigned in this experiment and are marked in red.

The higher-spin states from (41/2⁺) to (51/2⁺) in Seq.3 are then interpreted as 7- or 9-qp configurations

TABLE III: The two strongest components of wave functions and their partitions for the high-spin levels in CISM.

J^π	protons per orbital					Partitions (%)
	$0g_{7/2}$	$1d_{5/2}$	$1d_{3/2}$	$2s_{1/2}$	$0h_{11/2}$	
CISM_P1						
$39/2^+$	7	6	2	0	4	44
	7	6	0	0	6	18
$41/2^+$	8	5	2	0	4	46
	8	5	0	0	6	23
$43/2^+$	7	6	2	0	4	51
	8	4	1	0	6	11
$45/2_1^+$	7	5	1	0	6	62
	7	5	3	0	4	10
$45/2_2^+$	7	5	1	0	6	48
	7	5	3	0	4	23
$49/2_1^+$	7	5	1	0	6	76
	7	4	2	0	6	6
$49/2_2^+$	7	5	1	0	6	79
	7	3	3	0	6	6
$51/2_1^+$	7	5	1	0	6	78
	7	4	2	0	6	8
$51/2_2^+$	7	4	2	0	6	80
	7	5	1	0	6	7
$53/2^+$	7	4	2	0	6	90
	7	4	1	1	6	4
$55/2^+$	7	4	2	0	6	90
	7	4	1	1	6	4
CISM_N1						
$39/2^-$	8	5	1	0	5	67
	8	4	2	0	5	7
$41/2^-$	8	5	1	0	5	77
	8	3	3	0	5	3
$43/2^-$	8	5	1	0	5	75
	8	3	3	0	5	5
$45/2^-$	7	6	1	0	5	74
	7	4	3	0	5	8
$47/2^-$	7	5	2	0	5	46
	7	5	0	0	7	27
$49/2^-$	7	5	2	0	5	84
	7	4	2	1	5	4
$51/2^-$	7	5	2	0	5	88
	7	3	2	0	7	3
$53/2^-$	7	4	1	0	7	82
	7	4	3	0	5	11
CISM_N2						
$39/2^-$	8	5	1	0	5	71
	8	4	2	0	5	5
$41/2^-$	8	5	1	0	5	70
	8	3	1	0	7	4
$43/2^-$	7	6	1	0	5	64
	7	5	2	0	5	10
$45/2^-$	7	5	2	0	5	62
	7	5	0	0	7	11
$47/2^-$	8	4	2	0	5	76
	7	4	1	0	7	5
$49/2^-$	7	5	2	0	5	77
	7	5	1	1	5	8
$51/2^-$	7	5	1	1	5	71
	7	4	2	1	5	7
$53/2^-$	7	4	3	0	5	70
	7	4	1	0	7	12

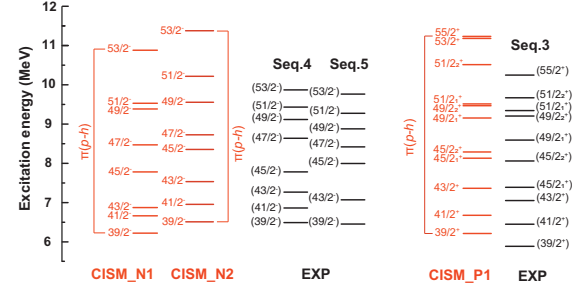


FIG. 11: CISM calculations of CISM in comparison with the experimental levels of Seq.3-5 in ^{151}Tm . The calculated levels and their configurations are marked in red.

including exciting one or two protons from the $g_{7/2}d_{5/2}$ to $h_{11/2}d_{3/2}s_{1/2}$ orbitals. The calculated levels with positive parities are labelled as CISM_P1 in Fig. 11. The occupancy numbers of them are listed in Table III. The levels above the $(39/2^+)$ state, are assigned as the multiplets of proton $p-h$ excitations across the $Z=64$ subshell closure. After the angular-momentum exhaustion in the $h_{11/2}$ orbital, the other orbitals in the $gdsh$ model space have same parities. Thus, the $\Delta I=1$ transitions connecting these levels are of M1/E2 character, consistent with their R_{AC} and R_{AD} values in Section III.C. The calculated excitation energies from $(39/2^+)$ to $(43/2^+)$ states of CISM_P1 are in reasonable agreement with 300 keV higher than the observed levels. They are dominant by the $\pi(1p-1h)$ excitations across the $Z = 64$ subshell with $J_{max} = (43/2^+)$. However, for the states above $(43/2^+)$, the deviation becomes even larger. The $(45/2_1^+)$ level at 7366 keV and the $(49/2_1^+)$ level at 8570 keV are about 800 keV lower than the CISM_P1 calculations. The states above $(51/2_1^+)$ in CISM_P1 show a large deviation with ~ 1 MeV higher than the experimental levels. This discrepancy indicates that they might be associated with the $N = 82$ neutron excitations and will be discussed together with the high-spin levels in Seq.4-5 as below.

SEQ.4-5 The CISM calculations for the states from $39/2^-$ to $53/2^-$ are presented in Fig. 11. For $2p-2h$ excitations across the $Z = 64$ gap in ^{151}Tm , the maximum spin is $51/2$, corresponding to the $\pi(h_{11/2})^5 \otimes \pi(d_{3/2}s_{1/2})(g_{7/2}^{-1}d_{5/2}^{-1})$ configuration.

For the states above it, additional proton excitations across the $Z = 64$ gap will give rise to a large energy gap (~ 1.5 MeV) between the $53/2^-$ and $51/2^-$ states in CISM (similar to the states above $(51/2^+)$ in Seq.3), which deviates significantly from the experimental observation. Therefore, for the states above $51/2$ in Seq.3-5, those that originated from proton excitations across the $Z = 64$ gap may not be yrast as the angular momenta of protons in the $h_{11/2}$ orbital are exhausted. Thus, neutron excitations across the $N = 82$ gap might be necessary and further shell model calculations including neutron excitations are needed.

SEQ.6 Since the 1050-keV de-exciting transition (following 24-ns isomer at 6909 keV) is not fully detected, the spin parities of levels in Seq.6 are not assigned and not compared with CISM calculations. As shown in Fig. 5, the final states at 9458 keV and 8745 keV in Seq. 6 are connected to the initial states (i.e., $(51/2_2^+)$ at 9670 keV and $(49/2_2^+)$ at 9184 keV) in Seq. 3. The final states at 9458 keV and 8745 keV in Seq. 6 may be associated with the neutron core excitations, similar to their initial ones in Seq. 3.

B. Possible neutron excitations across the $N = 82$ shell gap

In the $N = 82$ isotones with $Z < 64$, excited states of $\pi(g_{7/2}d_{5/2})^{Z-52}h_{11/2}^2$ and $\pi(g_{7/2}d_{5/2})^{Z-50} \otimes \nu(f_{7/2})(h_{11/2})^{-1}$ configurations are competing [14]. For nuclei with $Z > 64$, with the proton number increasing from 65 to 69, the proton Fermi surface rises and the occupancy number of $\pi h_{11/2}$ orbital increases, making it more difficult for protons to excite from $g_{7/2}$ and $d_{5/2}$ to $h_{11/2}$ orbits. Meanwhile, based on the mass measurements up to Tm and Yb nuclei [2, 34, 35], the $N = 82$ neutron shell gap has a rapid decreasing trend (6.5→4.0 MeV) as the proton number increases from $Z = 50 \rightarrow 58$ and a gradual decline (4.0→3.6 MeV) with $Z = 59 \rightarrow 70$. The observed overall reduction in the shell gap suggests that $N = 82$ neutron excitations are progressively facilitated in the high-spin states of $^{151}_{69}\text{Tm}_{82}$.

In Section A, the angular momenta of valence protons becomes exhausted after $\pi(2p-2h)$ excitation across the $Z = 64$ subshell, then neutron $p-h$ excitations might be involved in higher yrast levels with spin larger than $(51/2)$. In Seq.3-5, the observed states above $(51/2)$ are 1.5 MeV lower than the CISM calculated levels in the pure proton model space. Therefore, neutron excitations across the $N = 82$ shell gap might be involved in these states.

V. SUMMARY

The semimagic nucleus ^{151}Tm has been produced as a residue in the fusion evaporation reaction $^{58}\text{Ni} + ^{96}\text{Ru}$ at 266 and 274 MeV. A high-spin level scheme has been built by analyzing the $\gamma\text{-}\gamma$ coincidence data obtained with the JUROGAM array. In order to identify the new transitions of ^{151}Tm , we have also used their coincidences with isomeric transitions detected by the focal plane detectors of GREAT. Moreover, all the observed states have been compared to the results of CISM calculations. Most of the yrast states are well reproduced by these calculations. A contribution of neutron excitations across the $N = 82$ shell gap in the high-spin states (above $51/2$) of ^{151}Tm is tentatively assigned and further calculations for neutron excitations across the $N = 82$ shell gap are needed.

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