Level scheme in ^{160}Tm towards complete high-spin structure*

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Abstract High-spin states of ^{160}Tm have been studied through the ^{146}Nd(^{19}F, 5n) reaction at a beam energy of 102 MeV. The previously known $\pi h_{11/2}\otimes\nu i_{13/2}$ yrast band and $\pi h_{11/2}\otimes\nu h_{9/2}$ side band are confirmed, and several low-lying levels are observed. A 4-quasiparticle band feeding into the yrast band based on the $\pi g_{7/2}\otimes\nu h_{9/2}\otimes\nu i^2_{13/2}$ is suggested. Other two bands are observed and assigned to be based on the $\pi d_{3/2}\otimes\nu i_{13/2}$ and $\pi g_{7/2}\otimes\nu i_{13/2}$ configurations, respectively.

Key words high-spin states, level scheme, low-lying level, 4-quasiparticle

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1 Introduction

Experimental studies of odd-odd nuclei are generally difficult because of high level density at low-lying states. In well-deformed odd-odd nuclei, rotational bands based on 2-quasiparticle and 4-quasiparticle configurations, which are combinations of proton orbital and neutron orbital observed in neighboring odd-Z and odd-N nuclei respectively, are expected to be observed. In the systematic studies of high-spin states in odd-odd Tm isotopes, a number of such rotational bands have been reported in ^{162}Tm[1], ^{164}Tm[2] and ^{166}Tm[3]. However, up to now, only two isolated 2-quasiparticle bands based on $\pi h_{11/2}\otimes\nu i_{13/2}$ and $\pi h_{11/2}\otimes\nu h_{9/2}$ configurations are reported[4, 5] in ^{160}Tm. Comparing previous structure, a relatively completed level scheme in ^{160}Tm is reported here.

2 Experiment

States in ^{160}Tm nucleus were populated using the ^{146}Nd(^{19}F, 5n) reaction. A 1.6 mg/cm^2 self- supporting metallic ^{146}Nd target with an enrichment of 98% was bombarded with a 102 MeV ^{19}F beam delivered by the HI-13 tandem accelerator of CIAE in Beijing. The γ-γ coincidence events were collected with an array of twelve Compton-suppressed HPGe detectors. The energy and efficiency calibrations were made by using ^{60}Co and ^{152}Eu standard radioactive sources respectively. Typical energy resolutions of the detectors are about 2.0~2.5 keV at full width of half maximum for the 1332.5 keV γ ray.

A total of about 160×10^6 coincidence events were collected and sorted into a symmetric $\boldsymbol{E}_\gamma$-$\boldsymbol{E}_\gamma$ matrix for off-line analysis. To obtain multipolarity information of emitting γ-ray, an angular distribution experi-

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ment were also performed. The DCO $\boldsymbol{E}_\gamma$-$\boldsymbol{E}_\gamma$ matrix were created sorting on one axis the detectors lying at ±45°(±135°), and on the other those at ±90° with respect to the beam direction. The DCO ratios were calculated by the expression

$$R_{\rm DCO}=\frac{I_{\gamma1}(\text{at }45°;\text{ in coincidence with }\gamma_2\text{ at }90°)}{I_{\gamma1}\ (\text{at }90°;\text{ in coincidence with }\gamma_2\text{ at }45°)},$$

where γ_2 is normally a stretched E2(ΔI=2) transition, the $R_{\rm DCO}$ ≈1.0 for stretched quadrupole transitions and ≈0.5 for pure dipole ones. For averaging purposes and greater statistics, a summed coincidence spectrum from several successive E2 transitions was used whenever possible.

3 Experiment and discussion

On the basis of the analysis of the γ-γ coincidence relationships, rotational bands for ^{160}Tm are proposed and shown in Fig. 1. Spin and parity assignments of the $\pi h_{11/2}\otimes\nu i_{13/2}$ band (band A) and the $\pi h_{11/2}\otimes\nu h_{9/2}$ band (band B) are adopted from Refs. [4,5].

Several low-lying γ-rays in coincidence with the yrast band are observed. The DCO ratios obtained for 233.7 keV and 221.1 keV transitions are around 1.0, which require stretched quadrupole assignments, and are around 0.6 for 86.3 keV and 97.8 keV transitions which are consistent with ΔI=1 character. Most likely the (8$^-$) state that close to the bandhead of the yrast band de-excites the 74.5 s isomer of spin (5) via these transitions, and the decay path probably proceeds via an ΔI=3 transition to an intermediate state of spin (2) followed by an (M1+E2) or E1 transition to the g. s. ($I^\pi=1^-$) of ^{160}Tm[6]. The DCO ratios of the 191.8 keV and 128.9 keV transitions favor the spin assignment. The spins of other low-lying levels are given by DCO ratios and the multipolarity deduced from the internal conversion coefficients of the γ-rays on the intensity balance, temporarily.

Band C feeds into band A via the 513.5, 606.1, 704.5 and 801.9 keV transitions with DCO ratios of 0.97, 1.15, 0.97 and 1.11, respectively. The DCO ratios are consistent with stretched quadrupole character. These interband transitions are assumed to be of E2 character. If those transitions were of M2 character, they would represent a very unusual decay pattern where the M2 interband transitions would have comparable intensities with those of competing intraband M1 transitions. Based on these arguments, band C should have negative parity as that of band A and thus the spins of the levels in band C are fixed as shown in Fig. 1.

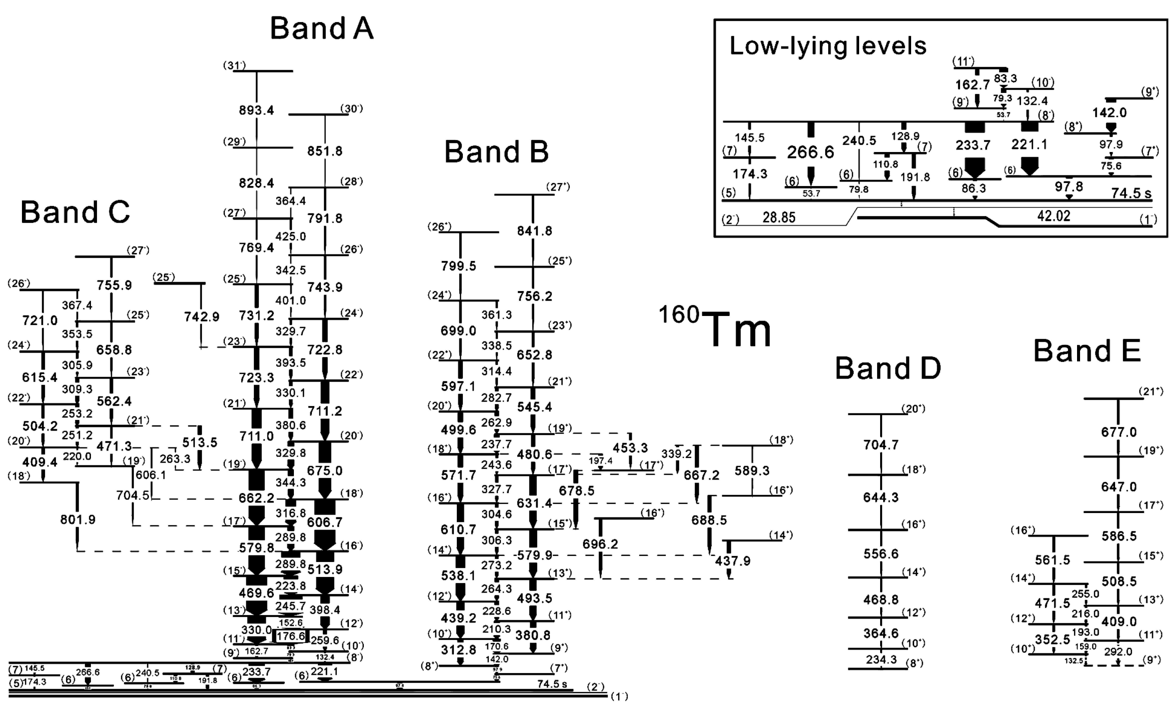

Fig. 1. Level scheme of ^{160}Tm proposed in this work. Low-lying part is enlarged in the insert.

Large and flat alignment, as show in Fig. 2, and the high-excitation energy of band C suggest that band C is a 4-quasiparticle structure involving the coupling of the odd neutron and odd proton with a pair of aligned $i_{13/2}$ quasi-neutrons. The crossing occurs in the unobserved initial part ($\hbar\omega \leqslant 0.25$ MeV) of band C must be AB crossing due to the BC crossing occurs at $\hbar\omega \geqslant 0.35$ MeV in the neighboring nuclei. The AB crossing is not blocked and thus the neutron does not occupy the $i_{13/2}$ orbital in the configuration of band C. Bands based on $i_{13/2}$ and $3/2^{-}[521]$ orbitals are strongly populated in the neighboring odd-neutron nuclei ^{159}Er[7] and ^{161}Yb[8], and the $3/2^{-}[521]$ orbitals are ground state in these two nuclei. It is most probable that the quasi-neutron of band C occupy the $3/2^{-}[521]$ orbital. To meet the requirement of negative parity of band C, the quasi-proton must occupy a positive parity proton orbital. Band based on $\pi g_{7/2}[404]7/2^{+}$ is the lowest and most strongly populated positive parity band in neighboring odd-proton nuclei ^{159}Tm[9] and ^{161}Tm[10], and bands based on positive orbitals $\pi d_{3/2}[411]1/2^{+}$ and $\pi d_{5/2}[402]5/2^{+}$ were also observed at higher energies and with lower intensities. All these arguments suggest that $\pi g_{7/2}\otimes\nu h_{9/2}\otimes(\nu i_{13/2})^2$ is the most favorable candidate for the configuration of band C.

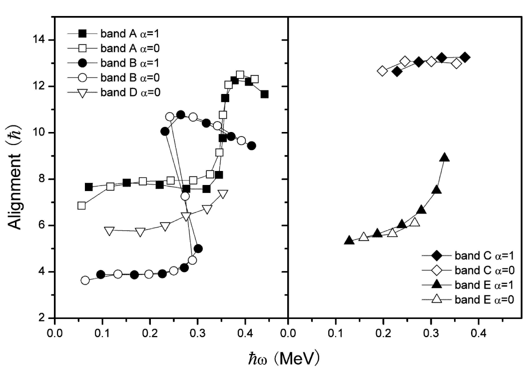

Fig. 2. Alignment of the bands in ^{160}Tm.

Comparing the alignment obtained for Band C (i_{bandC}) (see Fig. 2) with the sum of those corresponding to $\pi g_{7/2}[404]7/2^{+}(i_{\mathrm{p}})$, estimated from the average value of ^{159}Tm[9] and ^{161}Tm[10], the $h_{9/2}[521]3/2^{-}(i_{\mathrm{n}})$, estimated from the average value of ^{159}Er[7] and ^{161}Yb[8], and the alignment gain of the aligned $i_{13/2}$ quasi-neutron (i_{nn}), estimated from ^{160}Er[7], there is a good agreement,

$$i_{\mathrm{p}}+i_{\mathrm{n}}+i_{\mathrm{nn}}=0.5\hbar+2.6\hbar+9.4\hbar=12.5\hbar$$
vs. $i_{\mathrm{bandC}}=13.0\hbar$.

The experimental $B(\mathrm{M1})/B(\mathrm{E2})$ values are compared with the calculated for different possible configurations of band C based on the Cranking Shell Model, as given in Fig. 3. Parameters used in the theoretical calculations are listed in Table 1. These comparisons favor the configuration assignment $\pi g_{7/2}\otimes\nu h_{9/2}\otimes\nu i_{13/2})^2$ to band C. The band based on the same configuration is also observed in ^{162}Tm[1].

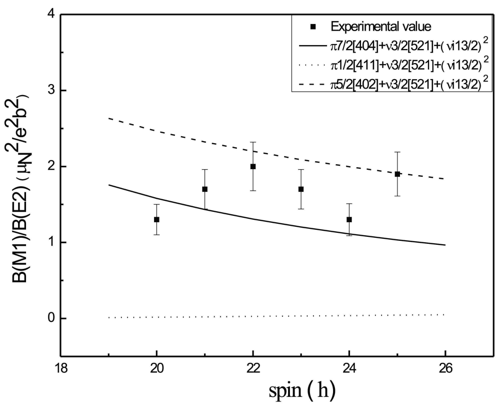

Fig. 3. Comparison of experimental $B(\mathrm{M1})/B(\mathrm{E2})$ ratios with the CSM calculated ones for defferent configurations.

Thus, the intrinsic configuration based on $\pi g_{7/2}[404]7/2^{+}\otimes\nu h_{9/2}[521]3/2^{-}\otimes(\nu i_{13/2})^2$ is suggested for band C.

Table 1. Parameters used in the theoretical $B(\mathrm{M1})/B(\mathrm{E2})$ calculations.

Configuration	$i_{\mathrm{n}}(i_{\mathrm{p}}, i_{\mathrm{nn}})(\hbar)$	$g_{\mathrm{n}}(g_{\mathrm{p}})$
$g_{7/2}[404]7/2^{+}$	0.5	0.73
$d_{3/2}[411]1/2^{+}$	0.2	−1.57
$d_{5/2}[402]5/2^{+}$	0.2	1.57
$h_{9/2}[521]3/2^{-}$	2.6	−0.17
$i_{13/2}$	9.4	−0.26
	g_{R}=0.30	Q_0=5.82 eb

Band D and band E observed in this work with about 10% intensity compared with band A are assigned to the nucleus ^{160}Tm. Other residual nuclei, such as ^{159}Tm (∼13%), ^{161}Tm (∼6.5%), ^{160}Er (∼15%), ^{157}Ho (∼2.5%), ^{159}Er (∼2.5%) and ^{158}Er (∼1.5%), are populated in present experiment, respectively. Level structures of these nuclei have been well known and investigated extensively.

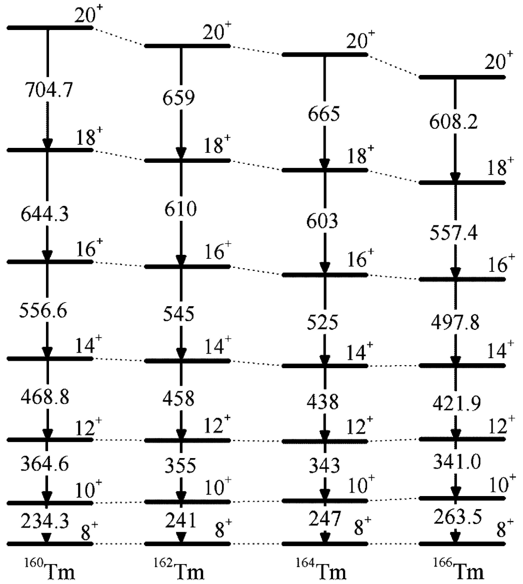

Fig. 4. Comparison of the favored sequences in the $\pi d_{3/2}\otimes\nu i_{13/2}$ bands of ^{160}Tm (this work), ^{162}Tm[1], ^{164}Tm[2] and ^{166}Tm[3]. Levels of $I^{\pi}=8^{+}$ are selected as references and the unit of energy is in keV.

On account of the population intensity of band D, the decoupled feature, highly aligned properties, delayed band crossing frequency, and systematic analyses, it is reasonably assigned to the nucleus ^{160}Tm. The observed only one signature partner suggests it decoupled feature, requiring the possible proton orbital arising from a state itself leading to a decoupled band, namely, either $h_{9/2}[541]1/2^{-}$ or $d_{3/2}[411]1/2^{+}$. The quasi-neutron arises from the $\nu i_{13/2}$ orbital. There is a good agreement with the experimental alignments ($i_{\rm pn}$=6.0$\hbar$) and the sum alignment of $\pi d_{3/2}$ and $\nu i_{13/2}$ band ($i_{\rm p}+i_{\rm n}$=0.5$\hbar$+5.6$\hbar$ = 6.1$\hbar$) extracted from the neighboring nuclei[8, 9], which supporting the configuration assignment of $\pi d_{3/2}\otimes\nu i_{13/2}$.

Figure 4 gives the comparison of the favored comparison of the favored sequences in the $\pi d_{3/2}\otimes\nu i_{13/2}$ bands of ^{160}Tm (this work), ^{162}Tm[1], ^{164}Tm[2] and ^{166}Tm[3]. The similarity in these structures indicates strongly that above assignments of nuclide and configuration are reasonable.

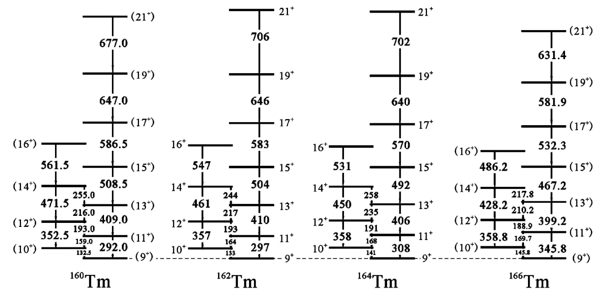

Fig. 5. Comparison of the $\pi d_{3/2}\otimes\nu i_{13/2}$ bands of ^{160}Tm (this work), ^{162}Tm[1], ^{164}Tm[2] and ^{166}Tm[3]. Levels of $I^{\pi}=9^{+}$ are selected as references and the unit of energy is in keV.

Band E is assigned to the nucleus ^{160}Tm based on the same discussion as band D. The delayed band crossing frequency indicates that the quasi-neutron arise from the $\nu i_{13/2}$ orbital. Only the $g_{7/2}[404]7/2^{+}$ and $d_{5/2}[402]5/2^{+}$ orbitals are candidate for proton. The $\pi g_{7/2}\otimes\nu i_{13/2}$ configuration is assigned to band E based on the energy level systematic comparison with the ^{162}Tm[1],^{164}Tm[2] and ^{166}Tm[3], as shown in Fig.5.

4 Conclusions

The previous level scheme of the ^{160}Tm are confirmed and enriched. Several low-lying levels are observed and bring a possible linking between the yrast band and low-lying states. Three new bands are observed. The configurations and spins of these bands are assigned with energy level systematics.

The investigation of the electromagnetism transition property and signature splitting feature in ^{160}Tm nucleus will be given in the forthcoming paper.

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