High spin states in ^{158}Dy

T. Hayakawa*
Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan and National Astronomical Observatory, Osawa, Mitaka, Tokyo 181-8588, Japan

Y. Toh, M. Oshima, M. Matsuda, Y. Hatsukawa, T. Shizuma, J. Katakura, and H. Iimura
Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan

S. Mitarai
Kyushu University, Hakozaki, Fukuoka 812-8581, Japan

Y. H. Zhang
Institute of Technology, Chinese Academy of Science, Lanzhou 730000, People's Republic of China

M. Sugawara
Chiba Institute of Technology, Narashino, Chiba 275-0023, Japan

H. Kusakari
Chiba University, Inage-ku, Chiba 263-8522, Japan
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High spin states in ^{158}Dy have been investigated using in-beam γ-ray spectroscopy techniques with the ^{150}Nd(^{12}C, 4n) reaction. Six rotational bands and several interband transitions have been observed. Sidebands have been discussed in terms of quasiparticle configurations.

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Nuclei located in a mass $A\sim150$ region are characterized by interplay of a collective rotational mode and other motions which are a quasiparticle excitation and a vibrational mode [1–3]. The nuclear deformation shows a gradual transition from a spherical shape in a closed shell to a prolate deformation with the increased neutron number [3]. Many rotational bands coupled with multiquasiparticle excitations in nuclei heavier than $N=91$ were reported using in-beam γ-ray spectroscopy techniques [4–14]. The nuclei also exhibit the octupole band structure, which consists of negative-parity rotational bands coupled with the octupole softness and strong $E1$ interband transitions between the octupole band and the ground-state band [3,15,16]. The octupole softness in small-deformed nuclei becomes large. Although the octupole bands in ^{160,162}Dy were previously known, those in ^{156,158}Dy whose deformation is smaller than that of ^{160,162}Dy were not reported. Riley *et al.* have identified many rotational bands in ^{156}Dy using in-beam γ-ray spectroscopy [17]. Two negative-parity sidebands were observed, which feed the ground-state band through several interband transitions. Although this structure suggested that the sidebands might be associated with the octupole bands, they were assigned rotational bands coupled with two quasiparticle excitations because their experimental Routhians and alignments were in agreement with the result of the Cranking shell model calculation. On the other hand, high spin states in ^{158}Dy were studied by fusion-evaporation reactions and nucleon-transfer reactions. Two sidebands which decay to the ground-state band through several interband transitions were reported [18–23]. Although the understanding of the character of the two sidebands has been important for the systematic study of the Dy isotopes, it has been unidentified because their parity and spin were not exactly established. The purpose of this study is investigation of high spin states in ^{158}Dy using in-beam γ-ray spectroscopy.

The ^{158}Dy nucleus was produced with the ^{150}Nd(^{12}C, 4n)^{158}Dy reaction. The ^{12}C beam with a 64 MeV energy was provided by the tandem accelerator at the Japan atomic energy research institute (JAERI). In order to detect γ rays with high energy resolution, the recoil nuclei were stopped in a thick target, which was a self-supporting metallic foil enriched to 96.1% with a thickness of 2 mg/cm^2. The γ rays from excited states were detected with an array, GEMINI [24], consisting of 12 HPGe detectors with BGO Compton suppressors. The HPGe detectors were placed at angles of 32°, 58°, 90°, 122°, and 148° with respect to the beam direction. The efficiencies of HPGe detectors were about 40%–70% relative to $3''\times3''$ NaI detector and the typical energy resolutions were 2.0–2.2 keV at 1.3 MeV. We recorded event by event the data when at least two HPGe detectors responded, and thereby we measured approximate 2×10^8 γ-γ coincidence events. The gated spectra were created from the matrices of 4096 chanel$\times$4096 channel. A level scheme was constructed from the coincidence relationship, the intensity balance, and the DCO ratios [25]. The relative intensities were derived from both the singles and gated spectra. The spin assignment was mainly made from

*Electronic address: hayakawa@jball4.tokai.jaeri.go.jp

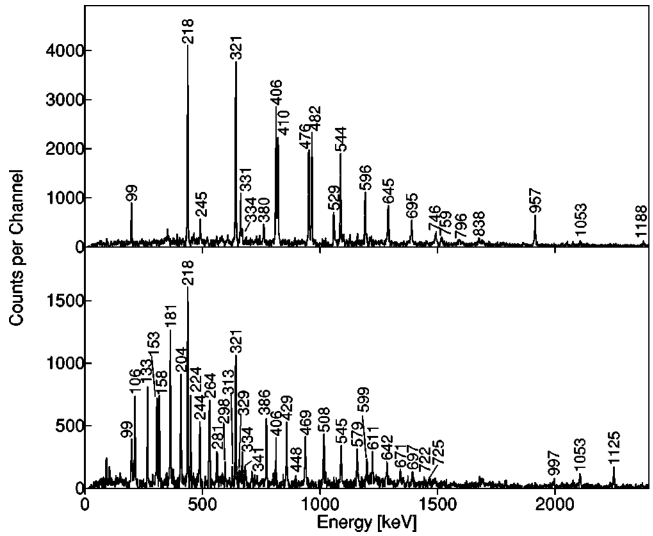

FIG. 1. Typical gated spectra in ^{158}Dy. (a) a sum spectra gated by the 331-, 596-, 645- and 695-keV γ ray in the band 2. We found newly two γ rays in the yrast states. (b) a sum spectra gated by the 133- and 158-keV γ ray for the band, 5 and 6. The $E2$ transitions and interband $M1$ transitions are shown.

the DCO ratios. Since the DCO ratio between 90° and 32° in our experiment setup was most sensitive, we used the DCO ratio defined by the following equation:

$$R_{DCO} = \frac{I(\gamma_1{:}32° \text{ or } 148° \text{ gated by } \gamma_2{:}90°)}{I(\gamma_1{:}90° \text{ gated by } \gamma_2{:}32° \text{ or } 148°)}.$$

The angle of 32° was equivalent to that of 148° for the DCO analysis [26]. Stretched $E2$ transitions close to the γ ray of interest with high excitation energy were used as gates.

Figure 1 shows some gated spectra, in which typical rotational bands are observed. A partial level scheme constructed from the result of the present experiment is shown in Fig. 2. The ground-stateband (band 1) and two sidebands (bands 2 and 3) were previously known [18], whereas bands 4, 5, and 6 are identified for the first time. Band 2 is extended by two new $E2$ transitions. Two transitions of 245 keV and 434 keV are newly placed in the lowest states of bands 2 and 3, respectively. Interband transitions between band 1 and sidebands were observed, which are important for the establishment of the spin and parity of the sidebands.

Figure 3 shows the DCO ratios of γ rays gated by $E2$ transitions. The DCO ratios of $\Delta I=0,2$ and $\Delta I=1$ dipole transitions are clearly separated from each other. Assuming pure dipole and quadrupole transitions, the DCO ratios of the $\Delta I=0,2$ transitions are nearly equal to 1.0, whereas that of the $\Delta I=1$ dipole transition is about 0.6. The spin and parity assignments for band 4 are important because bands 2 and 5, 6 feed band 4. The lowest state of band 4 feeds the 5^+ state via a 448-keV transition (see, Fig. 2). Since the 448-keV transition is assigned as a $\Delta I=1$ transition (see, Fig. 3), the possible spin and parity of the lowest state are $J^\pi=(6^+)$ or (6^-). If the parity was positive, one could observe $E2$ transitions linking between the lowest state and the 4^+ state of band 1 in the experiment. The most probable spin and parity are hence $J^\pi=(6^-)$. A 2476-keV excitation energy state of band 2 was assigned as $J=(10,11)$ in previous studies [18]. However this state is assigned as $J^\pi=(10^-)$ in the present experiment because this state feeds to the (8^-) level of band 4 through a 380-keV-γ ray which is assigned as an $E2$ transition. Band 2

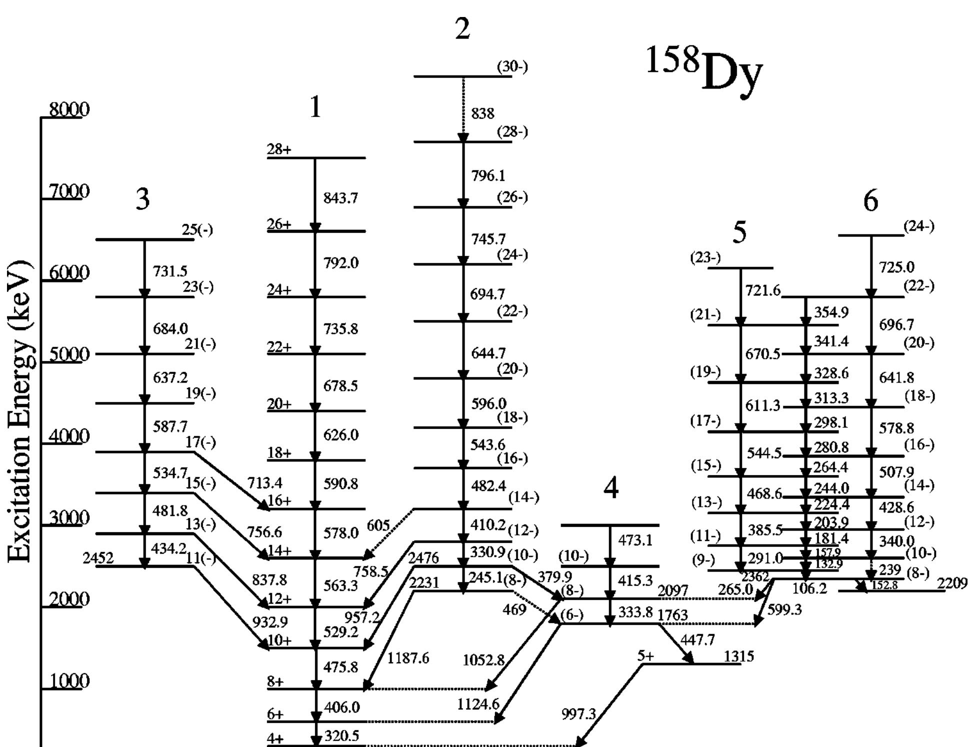

FIG. 2. Partial level scheme of ^{158}Dy constructed from the result of the present experiment. The six rotational bands and interband transitions are shown. Many interband transitions between sidebands and the ground-state bands were observed.

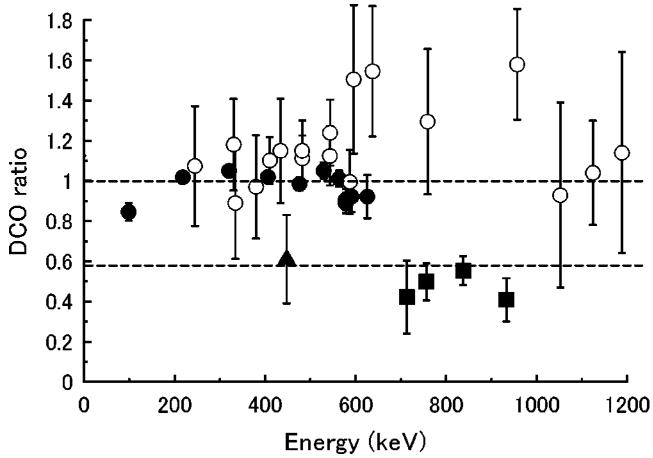

FIG. 3. The DCO ratios. Stretched $E2$ transitions close to the γ ray of interest with high excitation energy were used as gates. The DCO ratios of $\Delta I=2$ and $\Delta I=0$ transitions are nearly equal to 1.0, while the values of $\Delta I=1$ transitions are about 0.6. They are clearly separated from each other. Fulfilled circle means the $E2$ transitions in the ground-state band. Triangle means the 448 keV γ ray. Square means interband transitions from band 3 to the ground-state band.

also decays to band 1 via four interband transitions, which DCO ratios are consistent with the spin and parity assignments of the 2476-keV state. Band 3 feeds band 1 through four linking γ rays which are assigned as pure dipole transitions, and thus the bandhead of band 3 is assigned as $J^{\pi}=11^{(-)}$. The lowest state of band 6 and the (8^-) state of band 4 were measured previously by β-γ coincidence experiments [18]. Since the lowest state of band 6 feeds band 4 via two transitions, this state is tentatively assigned as $J^{\pi}=(8^-)$.

Although the octupole bands in the ^{156,158}Dy isotopes have not been reported, those in ^{160,162}Dy were identified. In addition the octupole bands in the ^{154}Sm, ^{156}Gd, ^{160}Er nuclei whose neutron numbers are same as that of ^{158}Dy were also reported [3,15,17,27]. Considering that bands 2 and 3 are assigned as negative-parity structures and that strong $E1$ interband transitions from these bands to the ground-state band were observed, it seems that bands 2 and 3 may be associated with the octupole band structure.

In this mass region, the identical bands were reported [5,8,28,29], which have the nearly identical transition energies within a few percent of each other. We reported the identical bands in $N=91$ isotones, ^{157}Dy, ^{155}Gd, and ^{153}Sm [29]. The yrast bands built on a $\nu i_{13/2}$ configuration in the $N=91$ isotones showed nearly identical γ-ray energies, but the transition energies of the ground-rotational bands of neighboring nuclei with $N=90$, which correspond to an even-even core of odd-N nuclei, were not identical. We therefore concluded that a shape driving force of the $i_{13/2}$ single neutron might introduce the manifestation of the identical bands [29]. The identical bands consisting of band 2 in ^{158}Dy and a two quasiparticle band in ^{156}Gd whose configuration has not been established were also reported in our previous paper [27]. The γ-ray energies of the two quasiparticle band in ^{156}Gd are 333-411-481-542-599 keV, while those in ^{158}Dy are 331-410-482-544-596 keV. Their energies are in agreement with each other within a few keV. We would like to stress that this fact suggests that band 2 can be associated with a rotational band coupled with two quasiparticle configuration involving the $i_{13/2}$([642]5/2) orbital neutron because of its shape driving force.

TABLE I. Convention for the labeling of quasineutron.

Label	(π,α)	Nilsson orbital
A	(+, +1/2)	$i_{13/2}$[642]5/2
B	(+, −1/2)	$i_{13/2}$[642]5/2
E	(−, +1/2)	$h_{9/2}$[521]3/2
F	(−, −1/2)	$h_{9/2}$[521]3/2
X	(−, +1/2)	$h_{11/2}$[505]11/2
Y	(−, −1/2)	$h_{11/2}$[505]11/2

The Nilsson orbitals near the Fermi surface in ^{158}Dy can be predicted by orbitals of single quasiparticle rotational bands in neighboring odd-N nuclei (see, Table I). Three rotational bands built on ν[642]5/2, ν[521]3/2, and ν[505]11/2 orbitals in $N=93$ isotones were reported [8,30]. The ν[642]5/2 and ν[521]3/2 configuration bands in these nuclei are the yrast states with the positive and negative parity, respectively. The experimental alignments and Routhians based on the present assignments of the spin and parity are plotted in Figs. 4 and 5, respectively. The ground-state band clearly shows the AB band crossing at the frequency of about 0.28 MeV (see, Table I). Since the alignments of bands 2 and 3 which are assigned as the negative-parity structures show no AB band crossing, they are expected to have AF and AE configurations (ν[642]5/2$\otimes\nu$[521]3/2), respectively. This assignment is consistent with the configuration indicated by the discussion concerning the identical bands. The strong interband transitions between the sidebands and the ground-state band can be explained by the coupling between the octupole softness and the quasiparticle excitations of the ν[642]5/2 and ν[521]3/2 orbitals. The strong $E1$ transitions between two rotational bands based on these orbitals in ^{157}Gd and

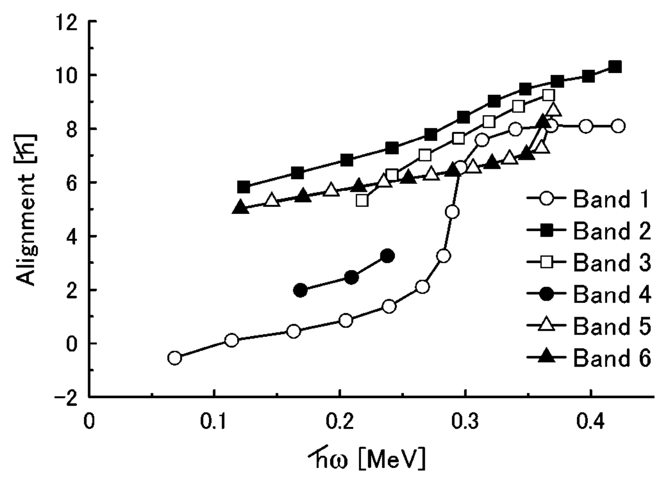

FIG. 4. Experimental alignments of ^{158}Dy derived from the present experiment. The Harris parameters $J_0=28.2\ \hbar^2$/MeV and $J_1=100\ \hbar^4$/MeV^3 are used. The ground-state band shows the AB band crossing at frequency of 0.28 MeV, whereas alignments of other bands show no clear band crossing.

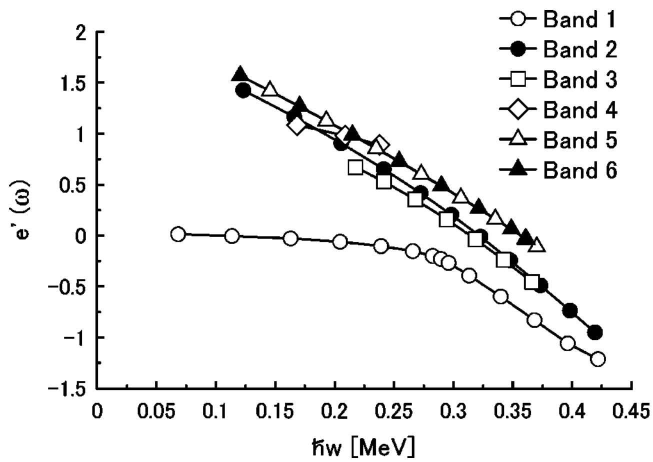

FIG. 5. Experimental Routhian of ^{158}Dy. The Harris parameters J_0=28.2 $\hbar^2$/MeV and J_1=100 $\hbar^4$/MeV^3 are also used. Routhian of bands 2 and 3 are almost same. This fact indicated that they are signature partners. A degeneration between bands 5 and 6 is shown, which is a feature of a strong-coupled band.

^{159}Dy reported in our previous experiments can be understood by introducing a parameter which effectively takes into account the octupole softness [30,31]. If bands 2 and 3 were associated with the octupole bands, we cannot explain the fact that band 2 and the sideband in ^{156}Gd have nearly identical transition energies. We thus conclude that bands 2 and 3 are interpreted as the signature partners of the two quasiparticle band build on the $\nu[642]5/2 \otimes \nu[521]3/2$ configuration.

Bands 5 and 6 exhibit a strong-coupled band structure comprising strong interband $M1$ transitions up to high spin states and two $E2$ cascades, indicating no signature splitting (see, Fig. 5). As shown Fig. 4, the alignments of bands 5 and 6 show the blocking effect for the AB band crossing. This fact suggests that this band structure can be associated with a rotational band based on two quasiparticle excitations of the [642]5/2 and a high-Ω orbital neutrons. In odd-A isotones many strong-coupled bands based on the $\nu[505]11/2$ orbital were reported [4,5,11,8,14,28]. In addition a similar band structure in ^{156}Dy was assigned the $\nu[651]3/2 \otimes \nu[505]11/2$ configuration band by comparing with the result of Cranking shell model calculation [17]. We therefore conclude that bands 5 and 6 are associated with the signature partners of the rotational band with the $\nu[642]5/2 \otimes \nu[505]11/2$ configuration (AX and AY).

In summary, high spin states of ^{158}Dy have been investigated by in-beam γ-ray spectroscopy using the ^{150}Nd(^{12}C, 4n) reaction. Six rotational bands and several interband transitions have been observed. A sideband which was previously known has been extended by two new $E2$ transitions. Two bands observed for the first time have been associated with signature partners of a strong-coupled band with the $\nu[642]5/2 \otimes \nu[505]11/2$ configuration. Two sidebands which were previously known have been tentatively assigned as even- and odd-spin components with negative parity in the present experiment. The experimental alignment property and the fact that the transition energies of the sideband and a two quasiparticle band in ^{156}Gd were nearly identical suggest that these bands are associated with two quasiparticle bands. We conclude that they are interpreted as signature partners of the two quasiparticle band with the $\nu[642]5/2 \otimes \nu[521]3/2$ configuration or the one coupled with the octupole softness because four sidebands based on the present experiment result can be consistently understood in terms of the coupling of the rotational motion and the two quasiparticle excitation.

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