Level structure and excitation energy of a high-spin isomer in ^{150}Ho

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The high-spin states of ^{150}Ho have been studied by the ^{141}Pr(^{16}O,7n)^{150}Ho reaction at a beam energy of 165 MeV using techniques of in-beam γ-ray spectroscopy. Measurements of γ-γ-t coincidences were performed. Based on the coincidence relations of γ rays, a level scheme was constructed up to 11.25 MeV. The excitation energy of high-spin isomer was determined to be 8.412 MeV with a half-life of 787 ± 36 ns. The experimental results were compared with deformed independent particle model (DIPM) calculations. The excitation energy of the state with the possible configuration of the high-spin isomer in ^{150}Ho was discussed.

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High-spin isomers were reported systematically in $N = 83$ isotones, ^{143}Nd, ^{144}Pm, ^{145}Sm, ^{146}Eu, ^{147}Gd, ^{148}Tb, ^{149}Dy, ^{150}Ho, and ^{151}Er [1]. Their lifetimes range from 10 ns to a few μsec. The excitation energies of high-spin isomers in $N = 83$ isotones are close each other in a range of 8.5–9.0 MeV. Their spins and parities are $J^\pi = 49/2^+$ and 27^+ for odd-A and odd-odd nuclei, respectively, except for ^{150}Ho and ^{151}Er. As to the ^{150}Ho nucleus, levels below the $J^\pi = 17^+$ isomer were established by McNeill *et al.* [2]. They *et al.* [3], reported the presence of the high-spin isomer around 8 MeV excitation energy, but data on the level scheme and spin-parity assignment were not enough to establish them. It is important to investigate the high-spin isomer in ^{150}Ho, since it has three $h_{11/2}$ valence protons which should largely contribute to the formation of the high-spin isomer. In order to determine excitation the energy of the high-spin isomer in ^{150}Ho, γ-ray spectroscopy experiment was carried out.

The experiment was performed at the Center for Nuclear Study (CNS) Tanashi, University of Tokyo. States in ^{150}Ho were populated using the reaction ^{141}Pr(^{16}O,7n)^{150}Ho. A self-supported natural ^{141}Pr target of 7.2 mg/cm^2 thickness was used. About 72% of reaction products were stopped in this thick target. The ^{16}O beam of 165 MeV was supplied by the SF-cyclotron with a repetition time of 108 ns. The average of the O^{4+} beam intensity was about 1 enA. The maximum angular momentum brought into the compound nucleus through the complete fusion process was calculated to be $\ell_{max} \sim 63\hbar$ using the Bass model [4]. The beam energy was chosen based on the statistical model code CASCADE calculation, and the predicted fusion cross section (30 mb) was consistent with the experimental result. For the γ-ray detection, five coaxial type HP Ge detectors with BGO anti-Compton shields were used. These detectors were placed at 45°, 70°, 90°, 125°, and 150° with respect to the beam axis. The distances between the target and the surfaces of the Ge detectors were about 100 mm. The total detection efficiency of γ ray was 0.1% at 1.3 MeV in the singles mode. A total of 5×10^8 γ-γ twofold coincidence events were recorded during 70 h in event-by-event mode for off-line analysis. The time width of the coincidence window is 2.5 μsec which corresponds to about 23 cyclotron beam repetitions.

Figure 1 shows proposed level scheme of ^{150}Ho. The level scheme above the 17^+ isomer is newly constructed. The widths of the arrows indicate γ-ray intensities, while the energies are given in keV units. A level scheme was extended up to the states at 11.25 MeV. Below the high-spin isomer, all coincidence relations were consistent with the previous report [5].

The half-life of the high-spin isomer was also extracted from the γ-γ-t data. Figure 2 shows the time distribution between the two γ-ray groups, which lie above and below the high-spin isomer, respectively. The decay counts were summed within time range of 108 ns which was the time period of the cyclotron natural beam bunching. A half-life of 787 ± 36 ns was extracted for the high-spin isomer from an exponential fit to the curve in Fig. 2. This result is consistent with the half-life reported in the previous report [2].

The 2^- ground and 9^+ isomeric states of ^{150}Ho mainly decay via allowed β-transitions to 2^+ and 8^+ states of the daughter nucleus ^{150}Dy. Excitation energy difference between 2^- ground- and 9^+ isomeric- states was determined to be about 500 keV from a measurement of the β-decay energy using a total γ-absorption spectroscopy method by Alkhazpf *et al.* [6]. The coincidence relations of known γ rays below the 17^+ isomer agree with those of the previous report [2].

Figure 3 displays background-subtracted γ-ray spectra in prompt coincidence with the 1059-keV transition. Thirty-four transitions which belong to ^{150}Ho were clearly identified. Transition energies of these γ rays are indicated in the spectrum. The peaks which have no energy label are γ rays from the other nuclei. The level scheme below the high-spin

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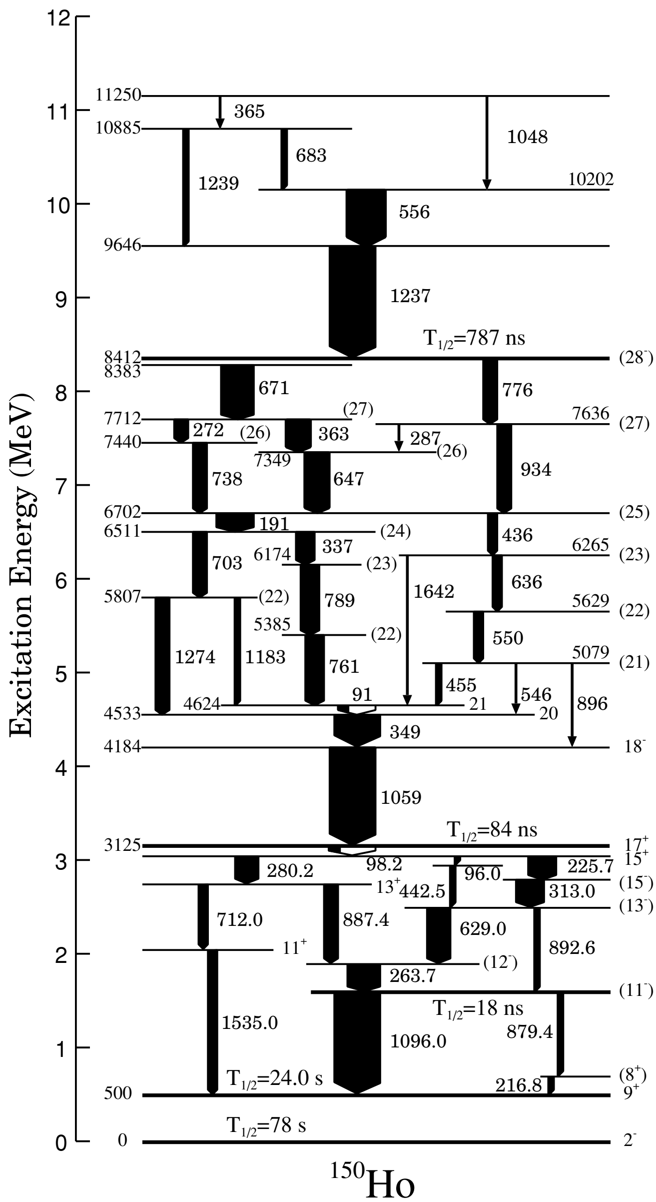

FIG. 1. The proposed level scheme for ^{150}Ho. The widths of arrows indicates γ-ray intensities. The level scheme above the 17^+ isomer are newly constructed. Isomeric states are shown by bold lines.

isomer in ^{150}Ho was constructed using the spectra gated on each γ-ray peak which is seen in Fig. 3. The ordering of each levels was determined considering the intensity balances and the coincidence relations of parallel cascades. Intensities and placements in the level scheme of all γ rays observed between 17^+ isomer and the high-spin isomer are given in Table I. The excitation energy of the high-spin isomer was determined to be 8.412 MeV.

For delayed coincidence analysis, a difference matrix was made by subtracting a post-prompt matrix from a preprompt matrix. A spectrum gated on a 1059-keV γ ray obtained from the difference matrix is shown in Fig. 4. The positive and negative peaks correspond to transitions above and below

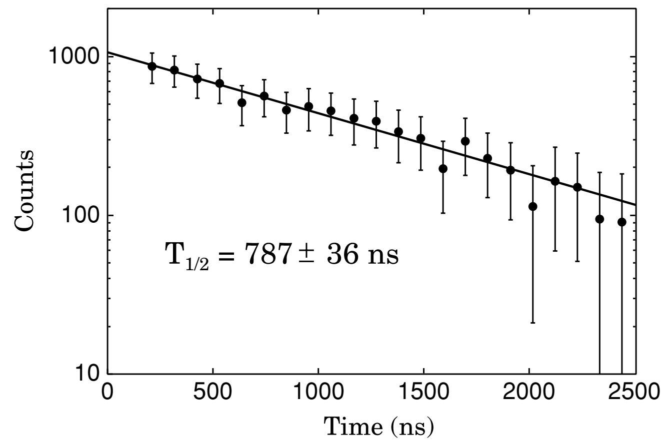

FIG. 2. The time distribution between the two γ-ray groups lying above and below the high-spin isomer.

the isomer, respectively. Two new γ-ray peaks which are transitions above the high-spin isomer are observed in this spectrum. Further, gating on the 1237-keV transition in prompt coincidence, five transitions are identified as those above the high-spin isomer. The level scheme above the high-spin isomer was constructed in the same manner as that used to make the level scheme below the high-spin isomer. Intensities and

TABLE I. Measured γ-ray energies, intensities, and spin changes of the states between 17^+ isomer and the high-spin isomer in ^{150}Ho. Relative intensities are normalized to the 1059 keV γ-ray intensity. Uncertainties are given in parentheses.

E_γ(keV)	I_γ	ΔI	$E_i \to E_f$	$J_i \to J_f$
91	16(7)		4624 → 4533	21 → 20
191	77(5)		6702 → 6511	
272	22(3)		7712 → 7440	
287	2(1)		7712 → 7349	
337	40(3)		6511 → 6174	
349	98(5)	2	4533 → 4184	$20 \to 18^-$
363	49(3)		7712 → 7349	
436	23(2)		6702 → 6265	
455	11(2)		5079 → 4624	
546	6(3)		5079 → 4533	
550	20(2)		5629 → 5079	
636	20(6)		6265 → 5629	
647	51(3)		7349 → 6702	
671	71(5)		8383 → 7712	
703	37(3)		6511 → 5807	
738	22(2)		7440 → 6702	
761	40(3)		5385 → 4624	
776	29(3)		8412 → 7636	
789	40(6)		6174 → 5385	
896	2(1)		5079 → 4184	
934	27(2)		7636 → 6702	
1059	100(5)	1	4184 → 3125	$18^- \to 17^+$
1183	11(2)		5807 → 4624	
1274	26(3)		5807 → 4533	
1642	3(1)		6265 → 4624	

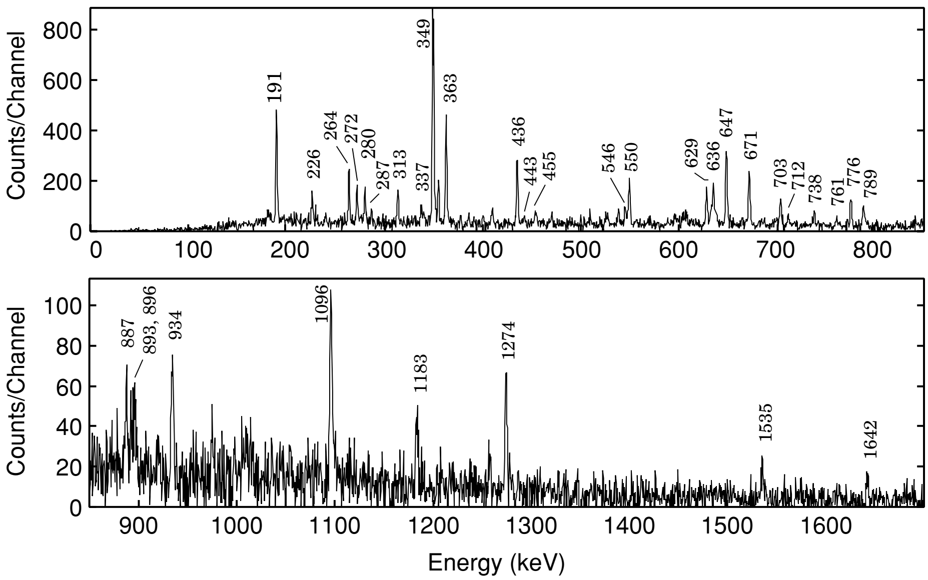

FIG. 3. Prompt spectrum gated by a 1059-keV γ ray. Transition energies of γ rays which belong to ^{150}Ho are indicated.

placements in the level scheme of all γ rays observed above the high-spin isomer are given in Table II.

The spin changes, ΔI, of 1059- and 349-keV transitions were assigned using the angular correlation. The A_2/A_0 value of the 1059–349 keV angular correlation was deduced to be –0.37(3). From this result, either 1059- or 349-keV transition should have $\Delta I = 2$ character. Assuming for the excited states of ^{150}Ho weak couplings of one proton to the excited states in ^{149}Dy, 1059-keV transition may have $E1$ character. The $M1$ character of 91-keV transition was extracted by the internal conversion coefficient which was obtained from the γ-ray intensity balance. These assignments are shown in Table I. Because of existence of the relatively long-lived isomers in ^{150}Ho, an angular distribution measurement are not effective for spin assignments. In addition, nuclei in this region have complex and irregular level structure. Therefore, large statistics are needed for angular correlation measurements than that in the present experiment.

It may be reasonable to understand that near yrast high-spin states of ^{150}Ho established in this work above the 17^+ states are resulted from weak couplings of one proton to those of ^{149}Dy. The configurations of high-spin states in ^{149}Dy were assigned in Ref. [7]. Considering a weak coupling of one proton in $h_{11/2}$ orbit, it is possible to understand the high-spin states in ^{150}Ho from 18^- to 21. As for the lower spin states up to the 17^+ isomer, the configurations of excited states were also discussed using a shell model calculation [2]. There are many parallel cascade transitions above the spin 20^- state. Since the similar parallel cascades were reported in ^{149}Dy above the $33/2^+$ state, this may indicate that they originate from weak couplings of a proton $d_{5/2}$ and $g_{7/2}$ hole to the states of ^{149}Dy [7]. Using a principle that for near yrast states the spin values of the excited states increase as excitation energies, the spin value of the high-spin isomer in ^{150}Ho reaches to 28 as shown in Fig. 1.

To understand the observed levels, a deformed independent particle model (DIPM) calculation [8] has been performed. The DIPM described well the yrast level structure of nuclei in the ^{146}Gd region. The calculations also reproduced the measured g-factors in ^{147}Gd [9] and ^{149}Dy [10] and quadrupole moments of the isomers in ^{146}Gd and ^{147}Gd [11]. The DIPM calculations also reproduce the energy systematics of the high-spin isomers in the $N = 83$ isotones changing the $Z = 64$ shell-gap energies [12]. Moreover, according to the DIPM calculations, the nuclear shape changes near spherical to oblate shape at the high-spin isomeric state. This sudden shape

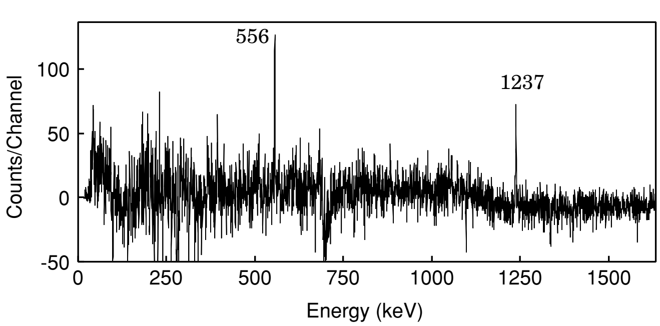

FIG. 4. A γ-ray spectrum made by gating on a 1059-keV transition of the difference matrix between a postprompt and a preprompt matrix.

TABLE II. Measured γ-ray energies, intensities above the high-spin isomer, Relative intensities are normalized to the 1237 keV γ-ray intensity. Uncertainties are given in parentheses.

E_γ(keV)	I_γ	$E_i \rightarrow E_f$
365	7(2)	11250 → 10885
556	82(6)	10202 → 9646
683	16(4)	10885 → 10202
1048	13(3)	11250 → 10202
1237	100(5)	9646 → 8412
1239	16(5)	10885 → 9646

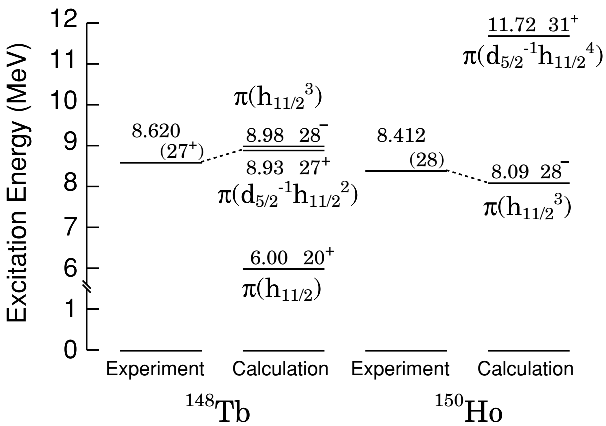

FIG. 5. Experimental and calculated excitation energies and configurations of states in ^{148}Tb and ^{150}Ho. The proton configurations are indicated. The neutron configuration is $\nu(f_{7/2}h_{9/2}i_{13/2})$ in all the cases. All configurations are maximum aligned states.

change causes the high-spin isomerism. This model was used to interpret the yrast level structure of ^{150}Ho.

From the DIPM calculation, the configuration of the high-spin isomers in the $Z < 64$ odd-odd isotones are deduced to be $[\nu(f_{7/2}h_{9/2}i_{13/2}) \otimes \pi(d_{5/2}^{-1}h_{11/2}^{2})]_{27^+}$. For the $Z > 64$ odd-odd nuclei, two kind of configurations are candidates of the high-spin isomers. One is a configuration with one proton hole as same as those of the $Z < 64$ odd-odd isotones. In another configuration, the angular momenta of all the protons which exist in the ground state are aligned, $[\nu(f_{7/2}h_{9/2}i_{13/2}) \otimes \pi(h_{11/2}^{n})]$. Where n is a number of valence protons. According to the DIPM calculation, excitation energies of these two configurations which are candidates of the high-spin isomer in ^{148}Tb were almost the same, 8.93 and 8.98 MeV. Therefore, it is difficult to decide the configuration of the high-spin isomer in ^{148}Tb from the excitation energy. On the other hand, in ^{150}Ho, energy difference of two candidates for the high-spin isomer are about 3.7 MeV. These two configurations are $[\nu(f_{7/2}h_{9/2}i_{13/2}) \otimes \pi(h_{11/2}^{3})]_{28^-}$ of 8.09 MeV and $[\nu(f_{7/2}h_{9/2}i_{13/2}) \otimes \pi(d_{5/2}^{-1}h_{11/2}^{4})]_{31^+}$ of 11.72 MeV excitation energy. Both configuration have the same degree of deformation, $\beta = -0.17$. In the oblate deformed state, single particle orbits originating from an $h_{11/2}$ orbit are not degenerate. In ^{150}Ho, three valence protons occupy these orbits from the low energy side. The above-mentioned energy difference results from the large excitation energy required to excite the fourth proton into the $h_{11/2}$ orbital from across the $Z = 64$ subshell gap. Experimental excitation energy of the high-spin isomer, 8.412 MeV, indicates the $[\nu(f_{7/2}h_{9/2}i_{13/2}) \otimes \pi(h_{11/2}^{3})]_{28^-}$ configuration. Experimental and calculated excitation energies and configurations for ^{148}Tb and ^{150}Ho are shown in Fig. 5. The spin and parity of the high-spin isomer is most likely to be $J^{\pi} = 28^-$ based on these considerations.

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