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Letter

Level structure of ^{146}Tb

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Abstract. The level structure of the doubly odd nucleus ^{146}Tb has been studied via the ^{118}Sn(^{32}S, 1p3n) reaction using techniques of in-beam γ-ray spectroscopy. Measurements of γ-ray anisotropies, X-γ and γ-γ-t coincidences were performed with 12 BGO(AC)HPGe detectors. Based on the measured results, the level scheme of ^{146}Tb has been revised significantly and extended up to an excitation energy of 8.39 MeV. The level structure has been interpreted qualitatively by coupling an $h_{11/2}$ proton-particle and an $h_{11/2}$ neutron-hole to the excited states in the ^{146}Gd core.

PACS. 23.20.Lv γ transitions and level energies – 27.60.+j $90 \leq A \leq 149$

The doubly odd nucleus ^{146}Tb has one proton-particle and one neutron-hole with respect to the doubly closed nucleus ^{146}Gd, and its high-spin states should be formed by excitations of valence nucleons. The low-lying states in ^{146}Tb are due to the couplings of one proton-particle with one neutron-hole outside ^{146}Gd. A number of such low-lying states have been identified in the previous in-beam studies [1,2] and in the β-decay studies of ^{146}Dy [3]. These low-lying energy levels can provide important information on the two-body residual interactions between proton-particle and neutron-hole. The higher-lying states should arise from the coupling of the valence proton-particle and neutron-hole to the excitations of the ^{146}Gd core. Before the present work, R. Collatz *et al.* have reported on a high-spin level scheme of ^{146}Tb using the ^{120}Sn(^{31}P, 5n) and ^{144}S(^{6}Li, 4n) reactions, and the level structure has been well interpreted by shell model calculations [2]. In the present paper, we report on a much revised level scheme for ^{146}Tb up to an excitation energy of 8.39 MeV.

We used the ^{118}Sn(^{32}S, 1p3n)^{146}Tb reaction to populate the excited states in ^{146}Tb. The ^{32}S beams were provided by the tandem accelerator at the Japan Atomic Energy Research Institute (JAERI). The target was an enriched ^{118}Sn metallic foil of 1.8 mg/cm^2 thickness with a 5 mg/cm^2 Pb backing. At the beam energy of 165 MeV, X-γ and γ-γ-t coincidence measurements were carried out with 12 BGO(AC)HPGe detectors, having energy resolutions of 1.9–2.3 keV at 1.33 MeV. To obtain γ-ray anisotropies, these detectors were divided into 3 groups positioned at 32° (148°), 58° (122°), and 90° with respect to the beam direction. All the detectors were calibrated using the standard ^{152}Eu and ^{133}Ba sources. A total of 300×10^6 coincidence events were accumulated. After accurate gain matching, these coincidence events were sorted into a symmetric matrix for off-line analysis. In order to extract information concerning γ-ray anisotropies, the coincidence data were sorted into two asymmetric matrices whose y-axis was the γ-ray energy deposited in the detectors at any angles and the x-axis was the γ-ray energy deposited in the detectors at 32°(148°) and 90°, respectively. By gating on the y-axes with suitable γ-rays, coincidence spectra at 32°(148°) and 90° were obtained. After efficiency calibration, γ-ray anisotropy was deduced from its intensity ratio in the two coincidence spectra. Typical γ-ray anisotropies observed for the known γ-rays in this experiment were 1.25 for stretched quadrupole transitions and 0.75 for stretched pure dipole transitions. Therefore we assigned the stretched quadrupole transition and

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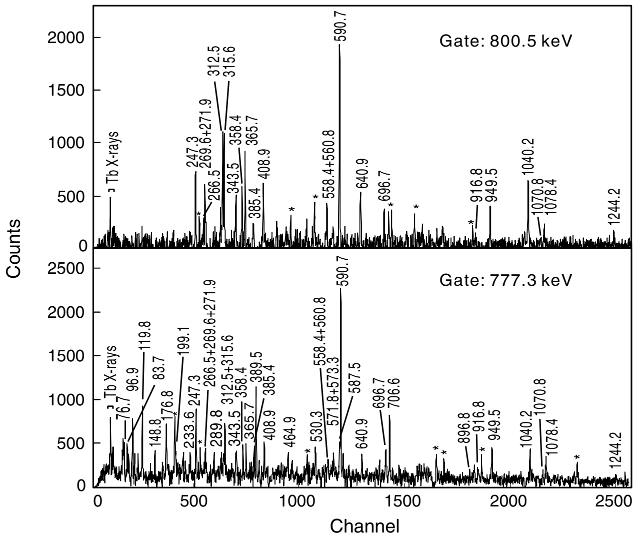

Fig. 1. Spectra of the γ-rays gated on the 777.3 and 800.5 keV transitions, respectively. The * symbols indicate contaminations.

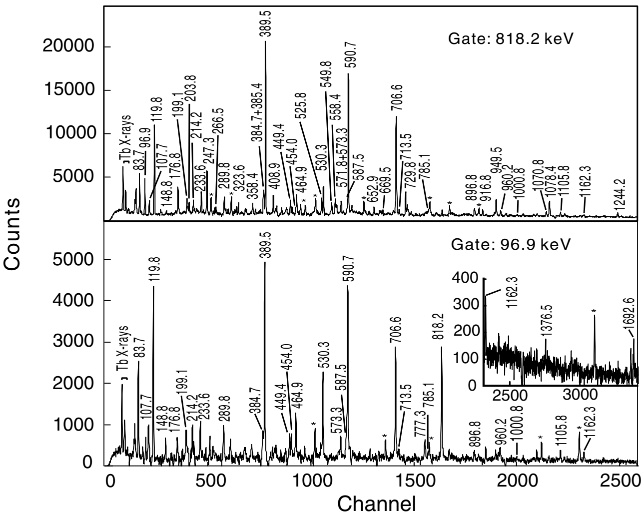

Fig. 2. Spectra of γ-rays gated on the 96.9 and 818.2 keV transitions, respectively. The * symbols indicate contaminations.

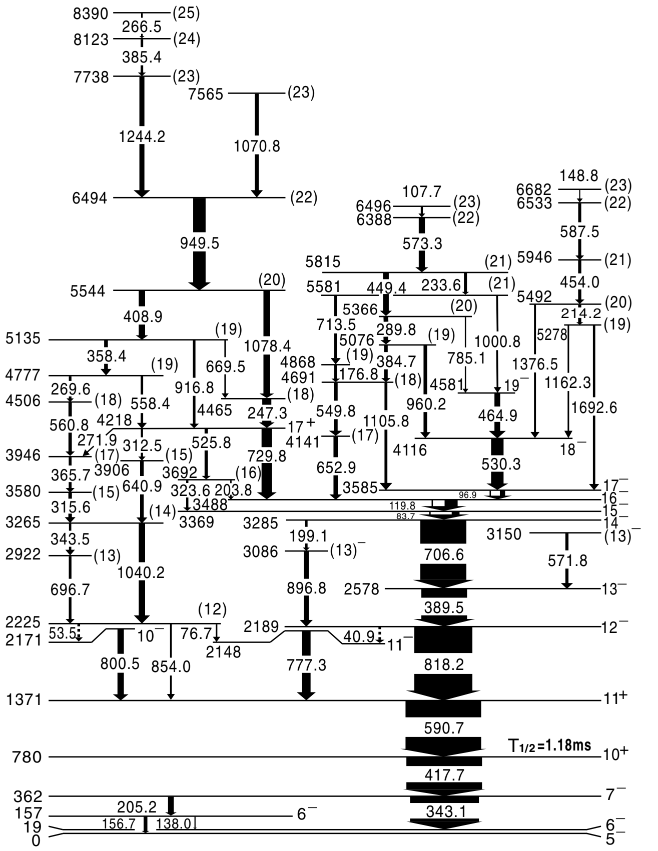

Fig. 3. Level scheme of ^{146}Tb deduced from the present work. The widths of the arrows indicate the relative transition intensities.

stretched dipole transition to the γ-rays of ^{146}Tb with anisotropies around 1.25 and 0.75, respectively.

Assignments of the observed γ-rays to ^{146}Tb were based on the coincidence relationships with the known γ-rays [2]. A gated spectrum was produced for each of the γ-rays assigned to ^{146}Tb. Selected spectra are shown in figs. 1 and 2. On the basis of the analysis of the γ-γ coincidence relationships, the level scheme of ^{146}Tb is extended up to an excitation energy of 8.39 Mev as shown in fig. 3, including 41 new γ-rays de-exciting 27 new levels. The orderings of the transitions in the level scheme are specified either with the help of some crossover transitions or from the consideration of the intensity balance in the gated spectra. The spins for the levels have been proposed according to the results of the γ-ray anisotropies and the previous conversion coefficient measurements [2].

The 442.7 keV transition depopulating the 805 keV state, as suggested in the previous study [2], cannot be confirmed in the present work. The state fed by the 590.7 keV transition was identified to be an isomer with configuration $\pi h_{11/2}\nu h_{11/2}^{-1}$ 10^+ [1]. All the γ-rays assigned to ^{146}Tb are in coincidence with the 590.7 keV transition. Thus, the present work suggests that the level scheme of ^{146}Tb is built on the $\pi h_{11/2}\nu h_{11/2}^{-1}$ 10^+ yrast isomer.

Figure 1 shows the spectra gated on the 777.3 and 800.5 keV γ-rays. The γ-rays in coincidence with the 800.5 keV line are observed for the first time, excpet for the 590.7 keV line. The γ-rays, shown in the spectrum gated by the 800.5 keV line, are also in coincidence with 76.7, 777.3 and 854.0 keV lines. As seen in fig. 1, the 777.3 keV transition is in coincidence with the 76.7 keV line but not with the 800.5 and 854.0 keV ones. The energy sum of the 777.3 and 76.7 keV transitions is 854.0 keV. Therefore, we presume that there exists a 53.5 keV transition connecting the 2225 and 2171 keV levels; this low-energy γ-ray cannot be observed due to its high conversion nature and low detection efficiency. The level scheme is divided into two separate parts above the 3488 keV level. Most of the γ-rays in the up-right part of the level scheme, as shown in the spectrum gated by the 96.9 keV line (fig. 2), are newly observed.

The level scheme of ^{146}Tb displays irregular level spacings and many parallel decay branches, indicating that the excited states are formed primarily by the excitations of valence nucleons. The ground state in ^{146}Tb has spin and parity of 5^-, and its configuration should be the admixture of the $\pi h_{11/2}\nu d_{3/2}^{-1}$ and $\pi h_{11/2}\nu s_{1/2}^{-1}$ configurations [4,5]. The low-lying states in ^{146}Tb have been well studied, and their configurations have been assigned based on shell model calculations [1,5]. The 10^+ and 11^+ yrast levels were interpreted to be the highest-angular-momentum members of the $\pi h_{11/2}\nu h_{11/2}^{-1}$ multiplet [2]. Obviously, the states above the 11^+ level should involve the excitations of the ^{146}Gd core. In ^{146}Gd, the first-excited state is the 3^- octupole state at 1579 keV, and the octupole excitation was suggested to have the main proton $h_{11/2}d_{3/2}^{-1}$ configuration with the admixture from the neutron $f_{7/2}s_{1/2}^{-1}$ and $h_{9/2}d_{3/2}^{-1}$ contributions [6,7]. Therefore, one would expect in ^{146}Tb a multiplet of negative-parity states of $\pi h_{11/2}\nu h_{11/2}^{-1} \otimes 3^-$ character at excitation energies around 2.5 MeV. The 10^-, 11^-, 12^-, and 13^- levels were suggested to be the members of the $\pi h_{11/2}\nu h_{11/2}^{-1}\otimes 3^-$ septuplet [2]. As mentioned above, the main component of the 3^- octupole excitation is the $h_{11/2}d_{5/2}^{-1}$ proton particle-hole configuration, which can couple with the $\pi h_{11/2}\nu h_{11/2}^{-1}$ to give a maximum spin of 13 only due to the Pauli-blocking principle. When the $\pi h_{11/2}\nu h_{11/2}^{-1}$ is coupled to the 3^- core state, the main $h_{11/2}d_{5/2}^{-1}$ component should be effectively blocked out by the Pauli principle in the 14^- state, and the energy of the 14^- state will consequently be pushed up. The excitation energy of the fully aligned $\pi h_{11/2}\nu h_{11/2}^{-1} \otimes 3^-$ state has been calculated by the method described in ref. [8] to be 3461 keV using the data from ^{147}Tb [9,10], ^{145}Gd [11], ^{146}Gd [6,7] and the 11^+ level in ^{146}Tb.

The high-spin states in ^{146}Tb are expected to arise from the coupling of a proton-particle and a neutron-hole to the ^{146}Gd core excitations. The $h_{11/2}$ orbits are available to both proton and neutron-hole, and the two $h_{11/2}$ orbits should play a dominant role in the particle-hole-core couplings due to their high-angular-momentum character. The magic shell closure for the protons at $Z = 64$ is weaker than the one for the neutrons at $N = 82$, and the protons can be easily excited across the $Z = 64$ shell gap. It has been identified experimentally that the yrast states up to 4 MeV in ^{146}Gd are formed by proton particle-hole excitations [12]. The negative-parity states with configurations $\pi h_{11/2}d_{5/2}^{-1}$ and $\pi h_{11/2}g_{7/2}^{-1}$ were observed in ^{146}Gd at excitation energies around 3 MeV [12]. Therefore, the negative-parity levels shown in the middle right-hand side of fig. 3 result probably from the $\pi h_{11/2}^2 d_{5/2}^{-1}\nu h_{11/2}^{-1}$ and $\pi h_{11/2}^2 g_{7/2}^{-1}\nu h_{11/2}^{-1}$ proton excitations. It has been pointed out [12] that there is little mixing between the $\pi h_{11/2}d_{5/2}^{-1}$ and $\pi h_{11/2}g_{7/2}^{-1}$ states in ^{146}Gd, and we propose here that this is also the case for the four quasi-particle states in ^{146}Tb. As discussed before, the excitation energy for the fully aligned $\pi h_{11/2}\nu h_{11/2}^{-1} \otimes 3^-$ state (14^-) is estimated to be 3461 keV, so the configuration $\pi h_{11/2}\nu h_{11/2}^{-1} \otimes 3^-$ might also contribute to the 14^- states observed experimentally. The first 2^+ and 4^+ states in ^{146}Gd were observed with excitation energies lower than the negative-parity levels of proton particle-hole excitations, and the main configurations $\pi s_{1/2}d_{5/2}^{-1}$ and $\pi d_{3/2}d_{5/2}^{-1}$ have been assigned, respectively [7,13]. It is likely that the excited states shown in the middle left-hand side of fig. 3 correspond to the $\pi h_{11/2}\nu h_{11/2}^{-1}\otimes 2^+$ and $\pi h_{11/2}\nu h_{11/2}^{-1} \otimes 4^+$ couplings. At high excitation energies, the $N = 82$ neutron shell closure might be broken, and the excitation patterns become complicated. It is difficult to discuss the configurations for the high-lying states.

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