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β-delayed proton decays and spin assignments for ^{140}Tb, ^{141}Dy and ^{143}Dy

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Abstract. The proton-rich isotopes ^{140}Tb and ^{141}Dy were produced via the fusion evaporation reaction ^{40}Ca + ^{106}Cd. Their β-delayed proton decays were studied by p-γ coincidence in combination with a He-jet tape transport system, and half-lives, proton energy spectra, γ-transitions following the proton emission, as well as β-delayed proton branching ratios to the low-lying states in the grand-daughter nuclei were determined. Comparing the experimental data with statistical model calculations, the ground-state spins of ^{140}Tb and ^{141}Dy were found to be consistent with 7 and 9/2, respectively. The configuration-constrained nuclear potential energy surfaces (NPES) of ^{140}Tb and ^{141}Dy were calculated using the Woods-Saxon-Strutinsky method, which suggest the ground-state spins and parities of ^{140}Tb and ^{141}Dy to be 7^+ and $9/2^-$, respectively. In addition, the configuration-constrained NPES of ^{143}Dy were calculated, which predict a $1/2^+$ ground state and a $11/2^-$ isomer with excitation energy of 198 keV. These findings are consistent with our previous experimental data on ^{143}Dy reported in Eur. Phys. J. A **16**, 347 (2003).

PACS. 23.40.Hc Relation with nuclear matrix elements and nuclear structure – 21.10.Hw Spin, parity, and isobaric spin – 24.10.Pa Thermal and statistical models – 27.60.+j $90 \leq A \leq 149$

Wilmarth *et al.* [1] studied the β-delayed proton (βp) decays of ^{140}Tb and ^{141}Dy near the proton drip line using the ISOL facility at LBL and reported the corresponding half-lives to be (2.4 ± 0.5) s and (0.9 ± 0.2) s, respectively. In addition, γ-rays of 329 and 508 keV were observed to follow the βp decay of ^{141}Dy, which corresponds to the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions in the grand-daughter nucleus ^{140}Gd. Later Gilat *et al.* [2] pointed out that the observed relative intensities of the 329 and 508 keV γ-rays observed in [1] are neither consistent with a $1/2^+$ nor with a $11/2^-$ assignment for the spin and parity of the precursor ^{141}Dy. Instead, Gilat *et al.* suggested the spin and parity of ^{141}Dy to be $9/2^-$, which was supported by their shell model calculation. The (EC + β^+) decay of ^{140}Tb was first observed by Firestone [3] and the spin and parity of ^{140}Tb was suggested to be 5^+. Detailed data for the (EC + β^+) decay of ^{140}Tb were reported by our group [4], including the (2.1 ± 0.4) s half-life for ^{140}Tb decay, and the spin and parity of ^{140}Tb was suggested to be 7^+ instead of 5^+. In the present work new studies on the βp decays of ^{140}Tb and ^{141}Dy are reported, and the final spin and parity assignments for ^{140}Tb and ^{141}Dy are proposed.

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The experiment described here was carried out at the Sector-Focusing Cyclotron in the Institute of Modern Physics, Lanzhou, China. A schematic view of the experimental set-up is shown in fig. 1 of ref. [5]. A 232 MeV $^{40}Ca^{12+}$ beam from the cyclotron entered a target chamber filled with 1 bar helium through a 1.89 mg/cm^2 thick Havar window. After traversing a 4.2 cm thick layer of helium gas and an aluminum degrader, the beam finally hits a ^{106}Cd target (75% enriched) of about 1.8 mg/cm^2. Four identical targets were mounted on a copper wheel surrounded by a cooling device, and the wheel was rotated by 90° once every 150 seconds. The beam energy in the middle of the target was 182 MeV, and the beam intensity was about 0.5 eμA. The ^{140}Tb and ^{141}Dy were produced via the αn (or 2p3n) and αpn (or 3p3n) evaporation channels, respectively. We used a helium jet in combination with a tape transport system to periodically move the radioactivity into a shielded counting room, using $PbCl_2$ at 430 °C as aerosol. The length of the capillary was about 6 m. The collection time, tape moving time, waiting time, and accumulation time were adjusted to 1.00, 0.16, 0.16, and 0.84 s, respectively. To study the β-delayed proton decays, proton-gamma coincidence measurements were carried out [6–8]. Two 570 mm^2 × 350 μm totally depleted

Table 1. Calculated and experimental relative branching ratios ($b_{\beta p}$) to different final states in ^{139}Eu from the βp decay of ^{140}Tb, assuming different values for the initial spin and parity of ^{140}Tb. The experimental relative $b_{\beta p}$ leading to the $15/2^-$ state was normalized to 30.

Initial spin and parity of ^{140}Tb	Relative $b_{\beta p}$ to the final states				
	G.S. $(11/2^-)$	323 keV $(15/2^-)$	427 keV $(13/2_1^-)$	531 keV $(13/2_2^-)$	877 keV $(19/2^-)$
6^-	66.9	13.0	12.1	7.9	0.1
6^+	63.3	14.2	13.4	8.8	0.2
7^-	46.5	27.8	15.1	9.7	0.9
7^+	45.6	29.5	14.6	9.6	0.7
8^-	28.9	44.4	13.4	8.7	4.5
8^+	24.7	43.6	15.6	10.3	5.7
Exp. value		30 ± 4	12 ± 3	8.5 ± 2	< 1

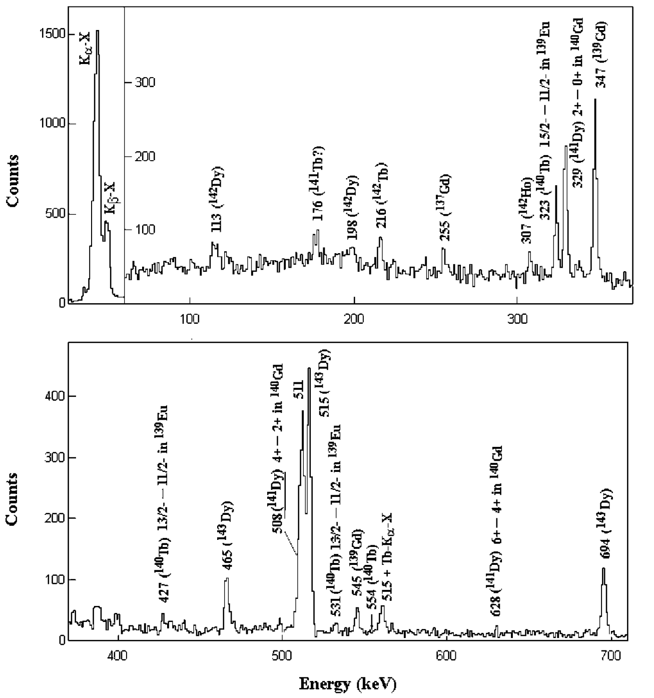

Fig. 1. The measured γ(X)-ray spectrum in coincidence with delayed protons from 3.0 to 7.0 MeV observed in the reaction ^{40}Ca + ^{106}Cd. The intense peaks are labeled by their energies in keV and their βp precursors.

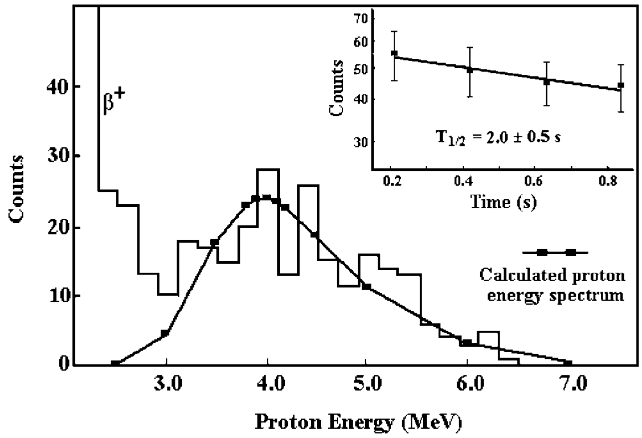

Fig. 2. The energy spectrum of β-delayed protons gated on the 323 keV γ line in ^{139}Eu (histogram: experimental result; solid line: statistical-model calculations assuming an initial spin of 7 for the βp precursor ^{140}Tb). The insert displays the decay curve of the 323 keV γ line gated on the β-delayed protons.

silicon surface barrier detectors located on two opposite sides of the movable tape were used to detect the protons. Behind each silicon detector a coaxial HpGe(GMX) was placed to observe γ(X)-rays. Energy and time spectra of γ(X)-rays and protons were recorded in both single and coincidence modes.

The observed γ(X)-ray spectrum gated on β-delayed protons of 3.0–7.0 MeV is shown in fig. 1. The intense peaks, except 511 keV and X-rays, are labeled with their energies in keV and their β-delayed proton precursors. In particular, the 323, 427 and 531 keV γ lines were assigned to the $15/2^- \rightarrow 11/2^-$ and to two different $13/2^- \rightarrow 11/2^-$ transitions in the proton daughter nucleus ^{139}Eu [9] following the βp decay of ^{140}Tb, while the 329, 508 and 628 keV γ lines were assigned to the $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions in the proton daughter nucleus ^{140}Gd [10] following the βp decay of ^{141}Dy. We did not observe a γ line at an energy of 554 keV, which would correspond to the $19/2^- \rightarrow 15/2^-$ transition in ^{139}Eu.

The energy spectrum of β-delayed protons gated on the 323 keV γ line of ^{139}Eu is shown in fig. 2, while the inset displays the decay curve of the 323 keV γ line when gated on the β-delayed protons. From the decay curve the half-life of ^{140}Tb was extracted to be (2.0 ± 0.5) s, which is consistent with the result given by Wilmarth *et al.* [1] as well as with our previous result reported in ref. [4].

The relative branching ratios ($b_{\beta p}$) to different final states in the proton daughter nucleus ^{139}Eu observed in the βp decay of ^{140}Tb and the proton energy spectra were calculated for various values of the initial spin and parity of ^{140}Tb using a statistical model [11], assuming a structureless Gamow-Teller (GT) β-strength function obtained from Gross theory [12]. The calculated $b_{\beta p}$ are listed in table 1 together with the experimental values, which were determined by means of the relative intensities of the correspondent γ lines in fig. 1. Unfortunately, we could not

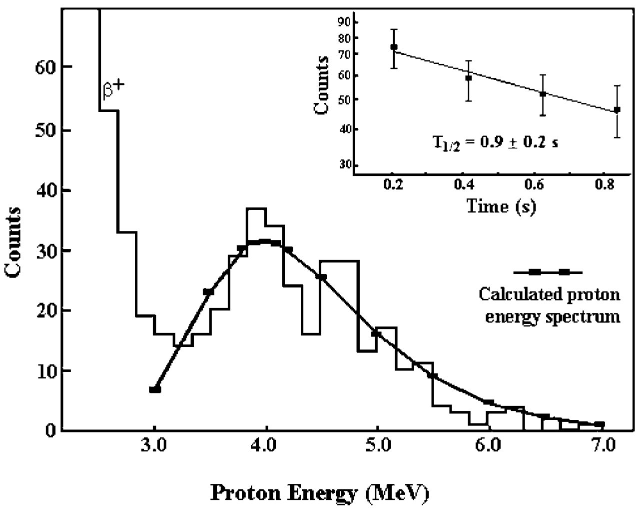

Fig. 3. The energy spectrum of β-delayed protons gated on the 329 keV γ line in ^{140}Gd (histogram: experimental result; solid line: statistical-model calculations assuming an initial spin of 9/2 for the βp precursor ^{141}Dy). The insert displays the decay curve of the 329 keV γ line gated on the β-delayed protons.

Table 2. Calculated and experimental relative branching ratios ($b_{\beta p}$) to different final states in ^{140}Gd from the βp decay of ^{141}Dy, assuming different values for the initial spin and parity of ^{141}Dy. The experimental relative $b_{\beta p}$ leading to the 2^+ state was normalized to 50.

Initial spin and parity of ^{141}Dy	Relative $b_{\beta p}$ to the final states			
	G. S. (0^+)	329 keV (2^+)	836 keV (4^+)	1464 keV (6^+)
$7/2^-$	18.0	59.4	22.1	0.4
$7/2^+$	12.8	64.0	22.5	0.7
$9/2^-$	4.9	49.2	41.1	4.8
$9/2^+$	9.5	48.6	38.8	3.1
$11/2^-$	3.9	32.3	50.1	13.6
$11/2^+$	1.2	29.3	55.3	14.3
Exp. value		50 ± 6	39 ± 8	7 ± 4

obtain the experimental $b_{\beta p}$ to the ground state in ^{139}Eu because of the restriction of the p-γ coincidence method. Comparing the calculated branching ratios with the experimental values, the closest agreement is found when assuming the ground-state spin and parity of ^{140}Tb to be 7^+ or 7^-. Moreover, the proton energy spectrum is reproduced reasonably well if ^{140}Tb is assumed to have 7^+ or 7^- (see fig. 2), the difference of the calculated energy spectra between the two parities being too small to be seen in fig. 2.

The energy spectrum of β-delayed protons gated on the 329 keV γ line of ^{140}Gd is shown in fig. 3, while the inset displays the decay curve of the 329 keV γ line when gated on the β-delayed protons. From the decay curve the half-life of ^{141}Dy was extracted to be (0.9 ± 0.2) s, which is consistent with the result given by Wilmarth *et al.* [1].

The relative $b_{\beta p}$ to different final states in the proton daughter nucleus ^{140}Gd observed in the β-delayed proton decay of ^{141}Dy and the proton energy spectra were also calculated for various values of the initial spin and parity of ^{140}Tb using the statistical model [11]. The calculated $b_{\beta p}$ are given in table 2 together with the experimental values. Comparing the calculated branching ratios with the experimental values, the closest agreement is found when assuming the ground-state spin and parity of ^{141}Dy to be $9/2^+$ or $9/2^-$. Moreover, the proton energy spectrum is reproduced reasonably well if ^{141}Dy is assumed to have $9/2^+$ or $9/2^-$ (see fig. 3), the difference of the calculated energy spectra between the two parities being too small to be seen in fig. 3.

To shed more light on the ground-state properties of ^{140}Tb and ^{141}Dy, the configuration-constrained NPES were calculated using the Woods-Saxon-Strutinsky method [13]. For ^{140}Tb a minimum at deformation parameters $\beta_2 = 0.243$ and $\gamma = 22.5°$ was found, which corresponds to the configuration $(\pi 5/2^-[532] \times \nu 9/2^-[514])$ 7^+, while for ^{141}Dy a minimum at $\beta_2 = 0.242$ and $\gamma = 21.5°$ was observed corresponding to the configuration $(\nu 9/2^-[514])$ $9/2^-$. These findings are not only in good agreement with the experimental results related to βp decay, but also with the spin assignments for ^{141}Dy given by Gilat *et al.* [2] and for ^{140}Tb as deduced in our previous study of the (EC + β^+) decay of ^{140}Tb [4]. We, therefore, assign 7^+ and $9/2^-$ to the ground state of ^{140}Tb and ^{141}Dy, respectively.

The ground-state spin and parity of ^{143}Dy was proposed as $1/2^+$ by Audi *et al.* [14] based on systematics and later supported by an in-beam γ study [15]. Moreover, the existence of an $11/2^-$ isomer with the energy of 310.7 keV was conjectured from these in-beam γ studies. Later, the decay of ^{143}Dy was observed and (EC + β^+) as well as βp decay schemes for the $1/2^+$ ground state and the $11/2^-$ isomer of ^{143}Dy were proposed by us in ref. [5]. Calculating the configuration-constrained NPES also for ^{143}Dy, a minimum at $\beta_2 = 0.202$ and $\gamma = 26°$ was obtained, which corresponds to the configuration of $\nu 1/2^+[400]$. In addition, a second minimum at $\beta_2 = 0.198$ and $\gamma = 47°$ was found, which corresponds to the spin assignment of $11/2^-$. Thus the NPES do support also our previous experimental results obtained for ^{143}Dy.

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