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(EC + β^+) decays of the $11/2^-$ isomer and $1/2^+$ ground state of ^{143}Dy

S.-W. Xu[a], Y.-X. Xie, Z.-K. Li, X.-D. Wang, B. Guo, C.-G. Leng, C.-F. Wang, and Y. Yu

Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, PRC

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Abstract. The $1/2^+$ ground state and a $11/2^-$ isomer of very neutron-deficient isotope ^{143}Dy were produced by irradiation of an enriched target of ^{106}Cd with ^{40}Ca and studied by using a helium-jet fast tape-transport system in combination with proton-γ, X-γ and γ-γ coincidence measurements. A simple (EC + β^+) decay scheme of ^{143m}Dy with a half-life of 3.0(3) s and a tentative (EC + β^+) decay scheme of ^{143g}Dy with a half-life of 5.6(10) s are proposed. As a by-product, the 347- and 545-keV γ transitions in ^{138}Sm following the β-delayed proton emission of ^{139}Gd decay and the 323-keV γ transition in ^{139}Eu following the β-delayed proton emission of ^{140}Tb decay could be observed for the first time.

PACS. 23.40.-s Beta decay; double beta decay; electron and muon capture – 21.10.Tg Lifetimes – 27.60.+j $90 \leq A \leq 149$

The first observation of the β-delayed proton decay of ^{143}Dy with proton energies of 2.0 MeV to 6.4 MeV was reported by Nitschke *et al.* in 1983 [1]. However, three different values for its half-life, 4.1(3) s [1], 3.2(6) s [2] and 3.8(6) s [3], were given by the same group. Recently, using an improved technique the result 3.2(6)s [2] of half-life was ascribed to the decay of the $1/2^+$ ground state of ^{143}Dy, and a possible $11/2^-$ isomer with an excitation energy of 310.7 keV was suggested to be populated in addition [4]. This assignment does not agree with the ground-state spin and parity of $3/2^-$ predicted for ^{143}Dy given by Möller *et al.* [5]. From a systematic point of view, however, the $1/2^+$ ground state and the $11/2^-$ isomer have already been observed in the isotopes ^{147}Dy and ^{145}Dy as well as in the isotones ^{141}Gd and ^{139}Sm. Using the Weisskopf estimate, the $E5$ transition probability from the $11/2^-$ isomer to the $1/2^+$ ground state of ^{143}Dy is estimated to be about 10^{-8}/s. It is thus feasible to have an (EC + β^+) decay directly from the $11/2^-$ isomer with a considerable long half-life. This work attempts to study the decay properties of both the $11/2^-$ isomer and the ground state of ^{143}Dy.

The experiment described here was carried out at the Sector-Focusing Cyclotron in the Institute of Modern Physics, Lanzhou, China. The sketch of the experimental set-up is shown in fig. 1. A 232-MeV $^{40}Ca^{12+}$ beam from the cyclotron entered a target chamber filled with 1 bar helium, passed through a 1.89 mg/cm^2 thick Havar window, a 4.2 cm thick layer of helium gas and an aluminum degrader, finally bombarded in turn four ^{106}Cd targets (75% enriched) with a thickness of about 1.8 mg/cm^2 each. The four targets were uniformly mounted on a copper wheel surrounded by a cooling device. The target wheel rotated by 90° once every 150 seconds. The beam energy at target center was 182 MeV. The beam intensity was about 0.5 eμA. The ^{143}Dy, ^{139}Gd and ^{140}Tb were produced via the 2pn, α2pn and αpn 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. $PbCl_2$ was used as aerosol at 430 °C. Two different experimental arrangements were used. One was the proton-gamma coincidence measurements for the study of the β-delayed proton decay [7–9], the other was the X-γ and γ-γ coincidences for the study of the EC/β^+-delayed γ-decay. In the proton-gamma coincidence measurements, the collection time, tape moving time, waiting time, and accumulation time were 5.00, 0.15, 0.15, and 4.85 s, respectively. Two 570 mm^2 × 350 μm totally depleted silicon surface barrier detectors were used for proton measurements, and located on two opposite sides of the movable tape. Behind each silicon detector a coaxial HpGe(GMX) was placed to observe γ(X)-rays. The energy and time spectra of γ(X)-ray and proton were taken in coincidence mode. In the X-γ and γ-γ coincidence measurements, normally the collection time, tape moving time, waiting time, and accumulation time were 8.30, 0.15, 0.30, and 8.00 s, respectively. Two coaxial HpGe(GMX)

[a] e-mail: xsw@ns.lzb.ac.cn

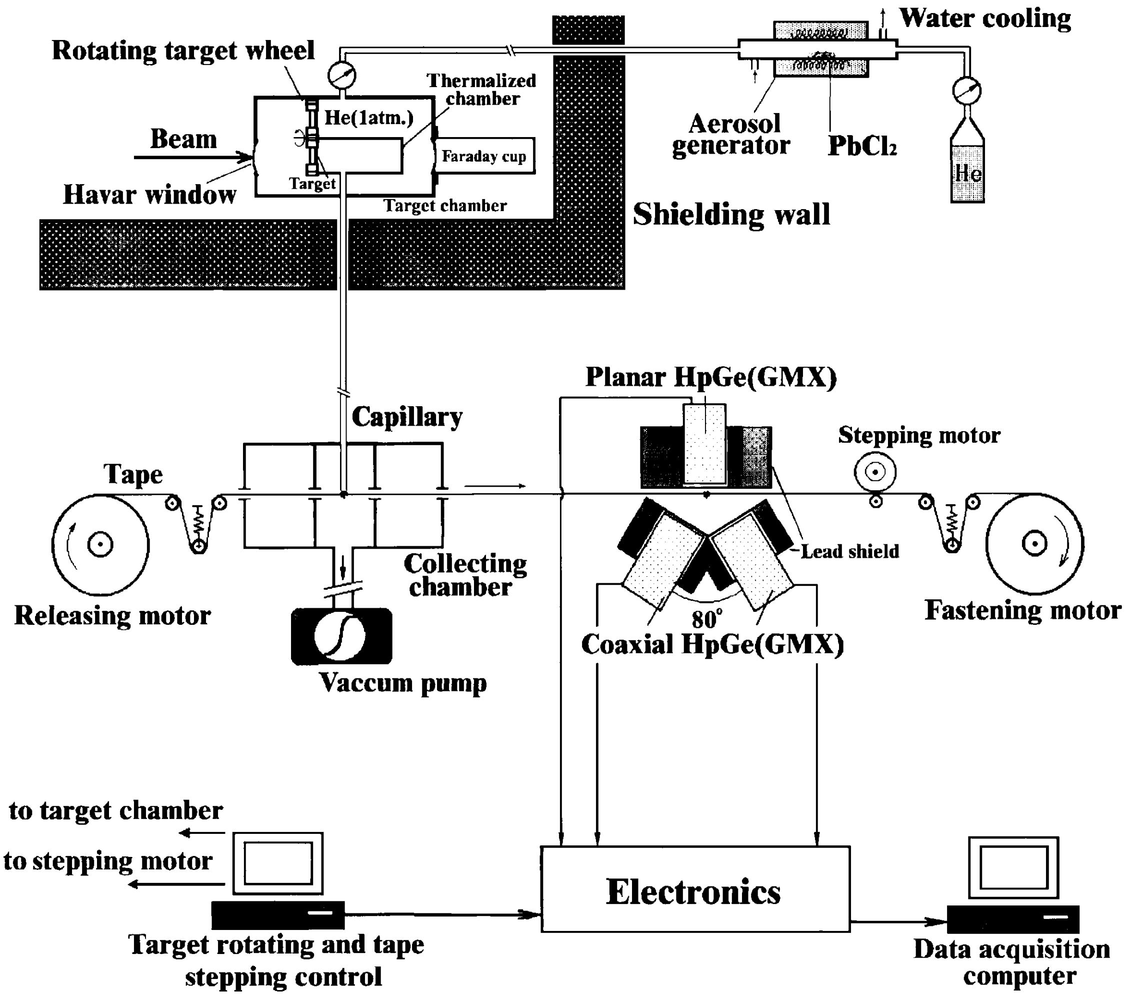

Fig. 1. The sketch of the experimental set-up for the X-γ and γ-γ coincidence measurements.

Table 1. Calculated relative branching ratios to different final states in the daughter nucleus ^{142}Gd via β-delayed proton decays of both the $11/2^-$ isomer and $1/2^+$ ground state of ^{143}Dy. $B_p = 1.12$ MeV.

Initial spin and parity of ^{143}Dy	Relative branching ratios to the final state (%)				
	Ground state (0^+)	515 keV (2_1^+)	980 keV (2_2^+)	1209 keV (4^+)	2003 keV (6^+)
$1/2^+$	72	23	5	~ 0	~ 0
$11/2^-$	1	32	8	53	6

detectors were used as γ-ray detectors and a HpGe planar detector was employed to detect X-rays. In order to improve the energy resolution for low-energy γ-rays, in some runs a second HpGe planar detector was used instead of a coaxial HpGe(GMX) detector. The energy and time spectra of γ- and X-rays were taken in single and coincidence modes.

The measured γ(X)-ray spectrum gated on 2.3–6.0 MeV protons is shown in fig. 2. All intense γ lines in fig. 2 could be assigned to their β-delayed proton precursors except the X-rays and the 511-keV γ-ray. Among them, the 515-keV γ line was assigned to the $2_1^+ \to 0^+$(ground state) transition in the daughter nucleus ^{142}Gd [10] of the proton emitter ^{143}Tb produced via the EC/β^+ decay of ^{143}Dy, and the 980-, 465-, 694-, and 794-keV γ lines in fig. 2 were attributed to the $2_2^+ \to 0^+$, $2_2^+ \to 2_1^+$, $4^+ \to 2_1^+$, and $6^+ \to 4^+$ transitions in ^{142}Gd [10], respectively. In addition, the 347- and 545-keV γ lines were assigned to the $2^+ \to 0^+$(ground state) and $4^+ \to 2^+$ transitions in the daughter nucleus ^{138}Sm [11] and to result from the EC/β^+-delayed proton decay of ^{139}Gd. The 323-keV γ line was assigned to the $15/2^- \to 11/2^-$transition in the daughter nucleus ^{139}Eu [12] populated via the (EC+β^+)-delayed proton decay of ^{140}Tb for

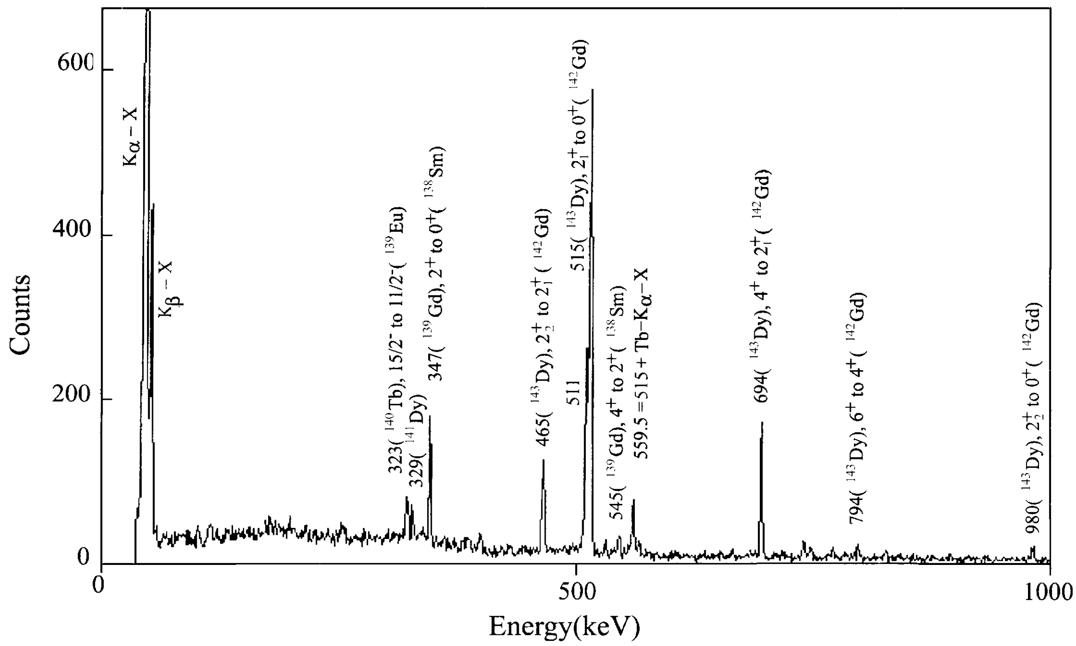

Fig. 2. The measured γ-ray spectrum in coincidence with 2.3- to 6.0-MeV protons. The intense peaks are labeled with their energies in keV and their β-delayed proton precursors.

the first time. This observation indicates that the ground-state spin of ^{140}Tb should be ≥ 5 which is consistent with our previous assignment of 7^+ [13].

The proton energy spectra gated on the 515- and 694-keV γ lines are shown in fig. 3. The components with energies below 2.0 MeV in the spectra were attributed to the pile-up of positrons in the silicon detectors. $\overline{E}_p$ in fig. 3 stands for the centroid of the energy spectrum. The decay curves of the 515- and 694-keV γ lines coincident with 2.3–6.0 MeV protons are shown in fig. 4. The relative branching ratios to different final states in the daughter nucleus ^{142}Gd via the β-delayed proton decay of both the $11/2^-$ isomer and $1/2^+$ground state of ^{143}Dy were calculated by using a revised statistical model [14,15]; the results are listed in table 1. Based on those calculations, the $2_1^+ \to 0^+$ transition in ^{142}Gd, *i.e.* the 515-keV γ line in fig. 2, is fed by the β-delayed proton decay of both the $1/2^+$ ground state and the $11/2^-$ isomer of ^{143}Dy, while the $4^+ \to 2_1^+$ transition in ^{142}Gd, *i.e.* the 694-keV γ transition in fig. 2, is caused by the $11/2^-$ isomer decay of ^{143}Dy only. Comparing the calculated relative branching ratios in table 1 with the observed relative intensities of 515-keV and 694-keV γ peaks in fig. 2, the components in the 515-keV γ transition from the β-delayed proton decay of both $11/2^-$ isomer and $1/2^+$ ground state were estimated to be almost equal, *i.e.* 50% each. Therefore, from the decay curve of the 694-keV γ line in fig. 4 the half-life of the $11/2^-$ isomer of ^{143}Dy can be extracted as 3.0 ± 0.5 s, and then from the decay curve of the 515-keV γ line in fig. 4 the half-life of the $1/2^+$ ground state of ^{143}Dy can be estimated as 6 ± 2 s.

Based on the X-γ coincidences and in-beam study of ^{143}Tb [16], the 521.1- and 541.5-keV γ lines, which correspond to the $13/2^- \to 11/2^-$ and $15/2^- \to 11/2^-$ transitions in ^{143}Tb, were assigned to the decay of the $11/2^-$ isomer of ^{143}Dy. With the aid of their excitation functions (fig. 5), also the three γ-rays of 142.8, 177.4 and 253.3 keV observed in the γ spectrum gated on the Tb-K_α X-ray were attributed to the (EC + β^+) decay of ^{143}Dy. The relative intensities and coincidence relationships of all γ transitions associated with the above five intense γ lines are listed in table 2. According to their coincidence relationships and their half-lives (see also fig. 6), the γ lines in table 2 except the 521.1- and 541.5-keV were divided into three groups: 1) (142.8–145.0)-keV γ lines with a half-life of 2.9(2) s; 2) (177.4–577.9–583.7)-keV γ lines with a half-life of 5.0(8) s; and 3) (113.7–253.3–428.2–440.3–533.5)-keV γ lines with a half-life of 5.7(9) s. In order to be consistent with the extracted half-lives in the β-delayed proton measurements, the first group of γ lines

Table 2. The relative intensities, coincidence relationships and half-lives of γ transitions in the (EC + β^+) decay of ^{143}Dy.

E_γ (keV)	I_γ	Coincident relations	Half-life
113.7(3)	34(8)	253.3	
142.8(3)	46(7)	145.0	2.9(2) s
145.0(3)	21(5)	142.8	
177.4(3)	62(7)	577.9, 583.7	5.0(8) s
253.3(3)	220(25)	113.7, 428.2, 440.3, 533.5	5.7(9) s
428.2(4)	46(9)	253.3	
440.3(4)	56(11)	253.3	
521.1(4)	58(11)		
533.5(4)	23(7)	253.3	
541.5(4)	100		3.1(3) s
577.9(4)	36(9)	177.4	
583.7(4)	100(14)	177.4	

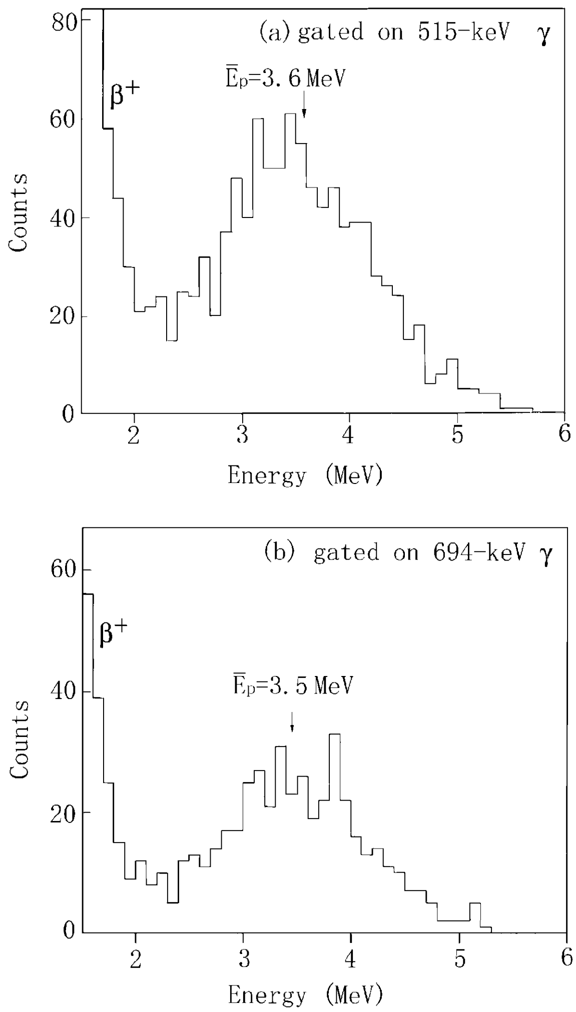

Fig. 3. Observed energy spectra of β-delayed protons gated by the 515-keV and 694-keV γ-rays.

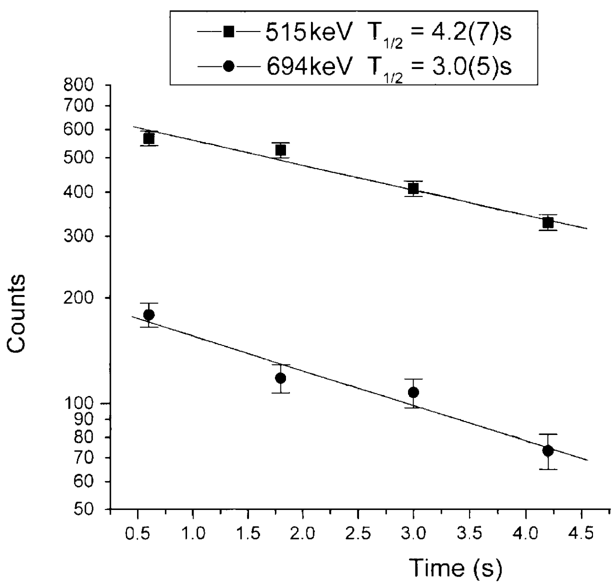

Fig. 4. The decay curves of the 515- and 694-keV γ lines coincident with 2.3–6.0 MeV protons.

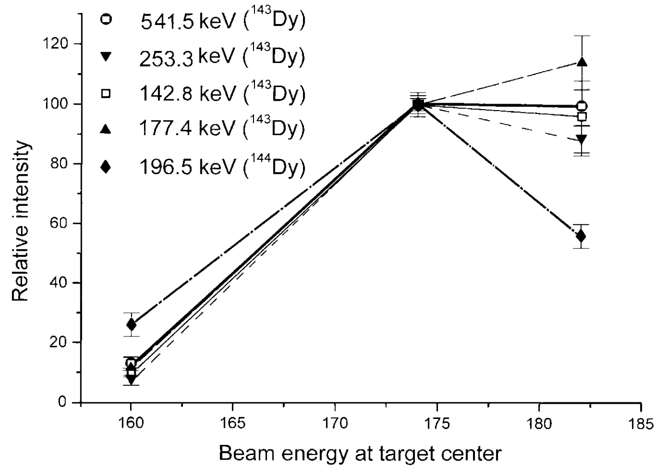

Fig. 5. The excitation functions of typical intense γ lines in the decays of ^{143}Dy and ^{144}Dy.

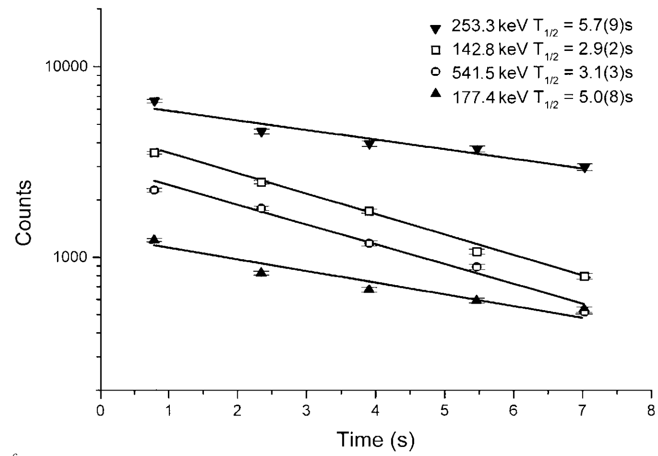

Fig. 6. The decay curves of the intense γ lines in the $(EC + \beta^+)$ decay of ^{143}Dy.

together with the 521.1- and 541.5-keV transitions were attributed to the $(EC + \beta^+)$ decay of the $11/2^-$ isomer of ^{143}Dy, while the second and third groups are tentatively assigned to the $(EC + \beta^+)$ decay of the $1/2^+$ ground state of ^{143}Dy. It should be noted that the 533.5-keV γ line (together with 10% intensity of 253.3-keV γ line) could eventually belong to the 253.7–534.5 keV cascade reported by Espinoza-Qinnoens *et al.* [17] to depopulate a $13/2^-$ state in ^{143}Tb. However, the intensity of the 533.5-keV γ line is too weak to determine its half-life. Further experimental studies are necessary to place the γ lines observed in the X-γ coincidences in the level scheme of ^{143}Tb.

A simple $(EC + \beta^+)$ decay scheme assigned to the $11/2^-$ isomer of ^{143}Dy and a tentative $(EC + \beta^+)$ decay scheme proposed to the $1/2^+$ ground state are shown in fig. 7(a) and fig. 7(b), respectively. From the half-lives observed from the 142.8-keV and the 541.5-keV transitions, an average value of 3.0(2) s for the half-life of the $11/2^-$ isomer of ^{143}Dy is deduced, while a half-life of 5.3(6) s is determined for the $1/2^+$ground state of ^{143}Dy from the decay curves of the 177.4-keV and 253.3-keV transitions.

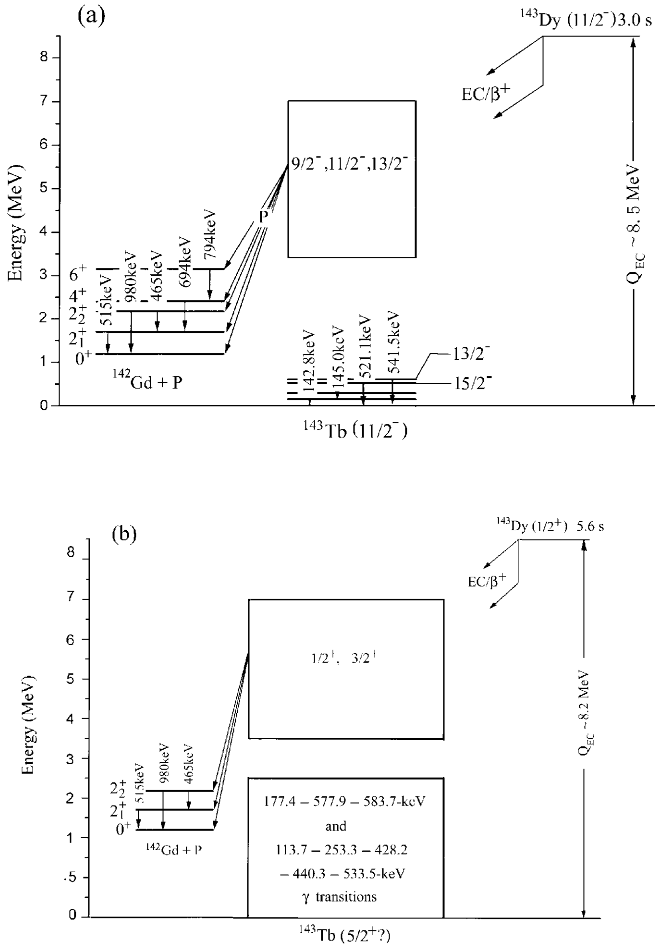

Fig. 7. (a) The proposed (EC + β^+) decay scheme of the $11/2^-$ isomer of ^{143}Dy. (b) The tentatively proposed (EC + β^+) decay scheme of the $1/2^+$ ground state of ^{143}Dy.

Both half-lives are in agreement with the respective half-lives extracted from the β-delayed proton measurements. Average values of 3.0 ± 0.3 s and 5.6 ± 1.0 s are finally adopted for the half-lives of the $11/2^-$ isomer and the $1/2^+$ ground state of ^{143}Dy, respectively.

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