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β-delayed proton decays and spin assignments for ^{133}Sm and ^{149}Yb

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Abstract. The proton-rich isotope ^{133}Sm was produced via the fusion evaporation reaction ^{40}Ca + ^{96}Ru. Its β-delayed proton decay was 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 nucleus were determined. Comparing the observed β-delayed proton branching ratios with statistical model calculations, the best agreement is found assuming that only one level with the spin of 3/2 in ^{133}Sm decays or two levels with the spins of 1/2 and 5/2 decay with similar half-lives. The configuration-constrained nuclear potential energy surfaces of ^{133}Sm were calculated using the Woods-Saxon-Strutinsky method, which suggests a $1/2^-$ ground state and a $5/2^+$ isomer with an excitation energy of 120 keV. Therefore, the simple (EC+β^+) decay scheme of ^{133}Sm in Eur. Phys. J. A **11**, 277 (2001) has been revised. In addition, our previous experimental data on the β-delayed proton decay of ^{149}Yb reported in Eur. Phys. J. A **12**, 1 (2001) was also analyzed using the same method. The spin-parity of ^{149}Yb is suggested to be $1/2^-$.

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 $90 \leq A \leq 149$

The β-delayed proton (βp) decay of ^{133}Sm was first studied by Bogdanov *et al.* [1] at Dubna in 1977. Its half-life was determined to be 3.2 ± 0.4 s. The spin and parity of ^{133}Sm was suggested to be $5/2^+$ only based on fitting the measured energy spectrum of β-delayed protons with statistical-model calculations. Experimental data on βp decay of ^{133}Sm measured by Wilmarth *et al.* [2] using an ISOL facility at LBL was reported in 1985. The half-life of ^{133}Sm was determined to be 2.8 ± 0.2 s. A 213 keV γ-ray following the βp decay of ^{133}Sm was observed, which corresponds to the transition between the lowest-energy 2^+ state to 0^+ ground state in the proton daughter nucleus ^{132}Nd. It was pointed out in [2] that according to a statistical-model calculation the branching ratio to 4^+ state in ^{132}Nd should be 12%, if the spin-parity of ^{133}Sm were $5/2^+$. However, a 389 keV γ-ray, *i.e.* the $4^+ \to 2^+$ transition in ^{132}Nd with an appropriate intensity was not seen. Therefore, the spin-parity assignment of $5/2^+$ to ^{133}Sm is less certain. On the other hand, only the two γ-rays of 369.6 and 156.8 keV with a half-life of 3.7 ± 0.7 s were assigned to the (EC+β^+) decay by Breitenbach *et al.* [3] in 1993. Later a simple (EC+β^+) decay scheme was proposed by our group [4] in 2001. According to the level scheme of ^{133}Pm given by Regan *et al.* [5], the 214.5 keV+X, 84.5 keV+X and 0.0 keV+X energy levels in our simple decay scheme (see fig. 1 in [4]) were assigned as $9/2^+$, $7/2^+$ and $5/2^+$, respectively. However, the level scheme of ^{133}Pm was improved and revised by Galindo-Uribarri *et al.* [6], and the spins and parities of the above three energy levels were assigned as $7/2^+$, $5/2^+$ and $3/2^+$ instead in ref. [6]. Of course, a similar revision should be made in our simple decay scheme. It should be noted that the β-delayed γ lines in our simple decay scheme could be separated into two isolated groups. The first group, including the 84.5 keV γ line, which corresponds to the $5/2^+ \to 3/2^+$ transition in the daughter nucleus ^{133}Pm, could be from a $5/2^+$ state of ^{133}Sm with a half-life of 2.8 ± 0.5 s. The half-life of another group which includes the 369.6 and 156.8 keV γ-rays was determined to be 3.4 ± 0.5 s, and seems different from the first one.

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In the present work, a new study on βp decay of ^{133}Sm is reported, and the spin-parity of ^{133}Sm is proposed. Comparing the βp decay and β-delayed γ decay, the simple (EC+β^+) decay scheme of ^{133}Sm in [4] is revised. In addition, our previous experimental data on βp decay of

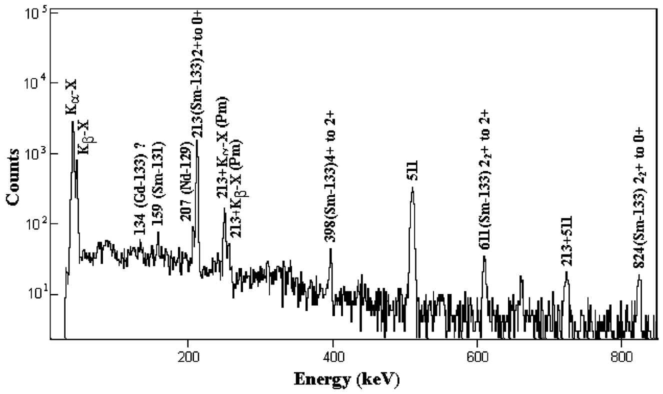

Fig. 1. The measured γ- and X-ray spectrum in coincidence with delayed protons of 2.5 to 6.0 MeV in the reaction ^{40}Ca + ^{96}Ru. The intense peaks are labeled by their energies in keV and their βp precursors.

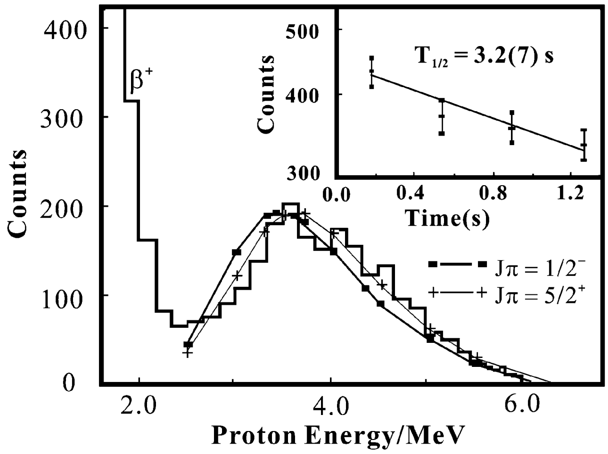

Fig. 2. The energy spectrum of β-delayed protons gated on the 213 keV γ line in ^{133}Sm. The histogram is the experimental result, while the curves stand for the statistical-model calculations. The inset displays the decay curve of the 213 keV line coincident with β-delayed protons.

^{149}Yb [7] was analyzed with statistical-model calculations, and a spin-parity of ^{149}Yb is proposed.

The experiment described here was carried out at the Sector-Focusing Cyclotron in the Institute of Modern Physics, Lanzhou, PRC. A schematic view of the experimental set-up is shown in fig. 1 of ref. [8]. A 232 MeV ^{40}Ca^{12+} beam entered a target chamber filled with 1 bar helium through a 1.89 mg/cm^2 thick Havar window. After traversing a layer of helium gas and an aluminium degrader, the beam finally hit on a ^{96}Ru target (85% enriched) with a thickness of about 1.4 mg/cm^2. The beam energy in the middle of the target was 180 MeV, and the beam intensity was about 40 pnA. The ^{133}Sm was produced via the 2pn evaporation channel. 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 is about 6 m. The collection time, tape moving time, waiting time, and accumulation time was adjusted to 1.60, 0.16, 0.16, and 1.44 s, respectively. In order to study the βp decay, proton-gamma coincidence measurements were carried out [8–10]. Two 570 mm^2 × 350 μm, totally depleted silicon surface barrier detectors located on 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- and X-ray. The energy and time spectra of γ- and X-rays as well as protons were recorded in both single and coincidence modes.

The observed γ- and X-ray spectrum gated on β-delayed protons of 2.5–6.0 MeV is shown in fig. 1. The intense peaks, except 511 keV and X-rays, are labeled with their energies in keV and their βp precursors. In particular, the most intense 213 keV γ line was assigned to the transition between the lowest-energy 2_1^+ state and 0^+ ground state in the proton daughter nucleus ^{132}Nd [11] following the βp decay of ^{133}Sm, while the 398, 611 and 824 keV γ lines were assigned to the $4^+ \to 2_1^+$, $2_2^+ \to 2_1^+$ and $2_2^+ \to 0^+$ transitions in ^{132}Nd [11], respectively.

The energy spectrum of β-delayed protons gated on the 213 keV γ line is shown in fig. 2, while the inset displays the decay curve of the 213 keV γ line when gated on the β-delayed protons. From the decay curve the "average" half-life of ^{133}Sm was extracted to be 3.2 ± 0.7 s.

Table 1. Calculated and experimental relative branching ratios ($b_{\beta p}$) to different final states in ^{132}Nd from the βp decay of ^{133}Sm, assuming different values of the initial spin and parity of ^{133}Sm. The experimental relative $b_{\beta p}$ leading to the 2_1^+ state was normalized to 50.

Initial spin and parity of ^{133}Sm	Relative $b_{\beta p}$ to the final states (%)			
	G. S.	213 keV	611 keV	824 keV
	(0^+)	(2_1^+)	(4^+)	(2_2^+)
$1/2^-$	56.6	39.6	0.5	3.3
$1/2^+$	51.3	43.5	1.1	4.0
$3/2^-$	37.7	54.0	3.7	4.7
$3/2^+$	38.3	54.1	2.4	5.2
$5/2^-$	22.5	60.9	11.1	5.5
$5/2^+$	15.8	64.2	13.7	6.3
Exp. Value		50 ± 4	3.0 ± 0.5	5 ± 1

The relative branching ratios ($b_{\beta p}$) to different final states in the proton daughter nucleus ^{132}Nd observed in the βp decay of ^{133}Sm for various values of the initial spin and parity of ^{133}Sm and the proton energy spectra were calculated using a revised statistical model [12,13]. The calculated results 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 obtain the experimental $b_{\beta p}$ to the ground state in ^{132}Nd because of the restriction of the p-γ coincidence method. Comparing the calculated branching ratios with the experimental values, the closest agreement is found assuming that only one level with the spin of 3/2 in ^{133}Sm decays or two levels with the spins of 1/2 and 5/2 decay with similar half-lives.

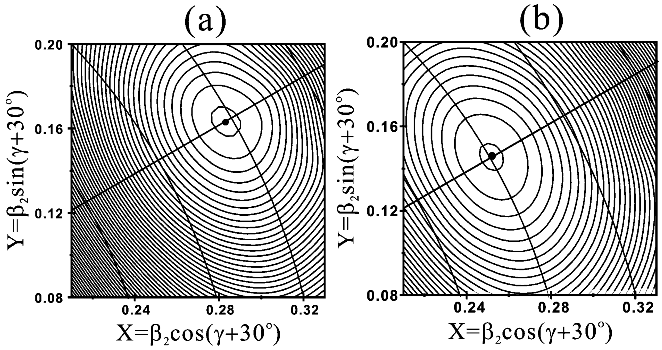

Fig. 3. Calculated nuclear potential energy surfaces of $1/2^-$ ground state (a) and $5/2^+$ isomer (b) for ^{133}Sm.

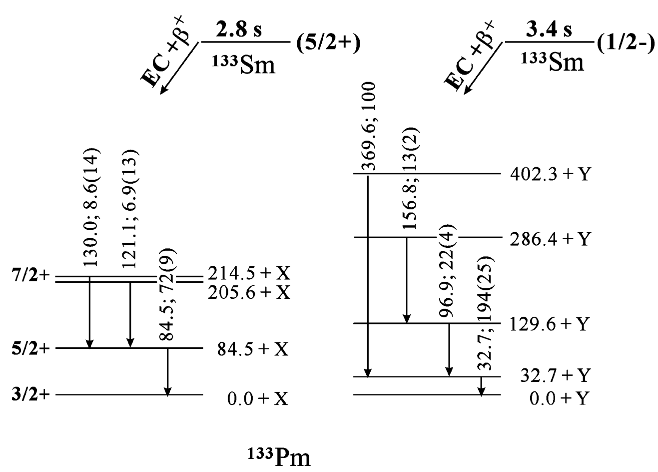

Fig. 4. Revised simple (EC+β^+) decay scheme of ^{133}Sm.

To shed more light on the ground-state properties of ^{133}Sm, the configuration-constrained nuclear potential energy surface (NPES) (fig. 3) was calculated by using the Woods-Saxon-Strutinsky method [14]. If the potential energy of ^{133}Sm is minimum, its shape has to be prolate, and the last neutron in ^{133}Sm is not able to occupy the obital of $\nu 3/2^+[402]$. Actually, a minimum at deformation parameters $\beta_2 = 0.327$ and $\gamma = -0.005°$ was found, which corresponds to the configuration $\nu 1/2^-[541]$ other than $\nu 3/2^+[402]$, and the second found out minimum at $\beta_2 = 0.291$ and $\gamma = 0.000°$ corresponds to the configuration of $\nu 5/2^+[402]$. The excitation energy of the minimum for the configuration of $\nu 5/2^+[402]$ is only 120 keV higher than that for the configuration of $\nu 1/2^-[541]$. In addition, the calculated energy spectra of β-delayed protons fit the experimental data well assuming two decaying levels in ^{133}Sm with spins and parities $1/2^-$ and $5/2^+$ (see fig. 2). Therefore, the spins and parities of the two decaying levels in ^{133}Sm were suggested to be $1/2^-$ (ground state) and $5/2^+$ (isomeric state). Comparing the calculated $b_{\beta p}$ and the experimental values, the relative decay intensities of $1/2^-$ state and $5/2^+$ state are $\sim 75\%$ and $\sim 25\%$, respectively. Finally, the simple (EC+β^+) decay scheme of ^{133}Sm in [4] should be separated into two components and revised in fig. 4. The first component of the (EC+β^+) decay with the half-life of 2.8 s, including the 84.5 keV γ line,

Table 2. Calculated and experimental relative branching ratios ($b_{\beta p}$) to different final states in ^{148}Er from the βp decay of ^{149}Yb, assuming different values of the initial spin and parity of ^{149}Yb. The experimental relative $b_{\beta p}$ leading to the 2^+ state was normalized to 50.

Initial spin and parity of ^{149}Yb	Relative $b_{\beta p}$ to the final states (%)		
	G. S. (0^+)	647 keV (2^+)	1524 keV (4^+)
$1/2^-$	83.0	16.8	0.2
$1/2^+$	77.7	22.1	0.2
$3/2^-$	70.0	29.3	0.7
$3/2^+$	70.7	28.8	0.5
$5/2^-$	55.3	42.2	2.4
$5/2^+$	49.8	47.2	3.0
Exp. Value		50	$\leqslant 1$

comes from the $5/2^+$ isomeric state in ^{133}Sm, while the second one with a half-life of 3.4 s, including the 369.6 and 156.8 keV γ lines, comes from the $1/2^-$ ground state. By the way, the "average" half-life of the 213 keV γ line gated on β-delayed protons is 3.2 s, somewhere between 2.8 and 3.4 s, because of the contributions of the two components.

The experimental data of βp decay of ^{149}Yb was reported for the first time by our group [7] in 2001. The relative $b_{\beta p}$ to different final states in the proton daughter nucleus ^{148}Er from the βp decay of ^{149}Yb for various values of the initial spin and parity of ^{149}Yb were calculated with the revised statistical model. The calculated $b_{\beta p}$ are listed in table 2 together with the experimental values. Comparing the calculated $b_{\beta p}$ with the experimental values, the initial spin and parity of ^{149}Yb could be 1/2 or 3/2. Recently, the configuration-constrained NPES of ^{149}Yb was calculated using the Woods-Saxon-Strutinsky method. A minimum with $\beta_2 = 0.166$ and $\gamma = 60°$ was found (fig. 5), which corresponds to the configuration of $\nu 1/2^-[521]$. In addition, the βp energy spectrum of ^{149}Yb

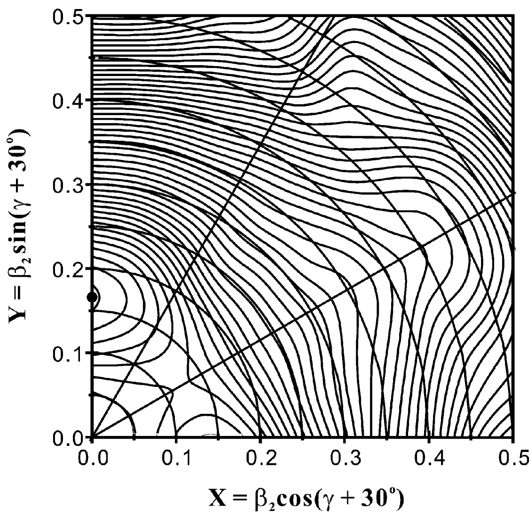

Fig. 5. Calculated nuclear potential energy surface for ^{149}Yb.

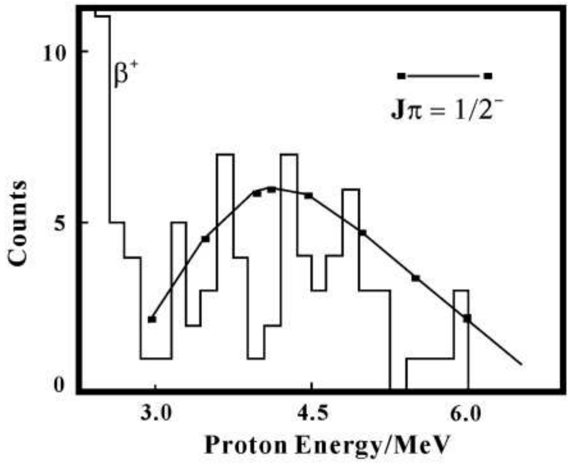

Fig. 6. The energy spectrum of β-delayed protons gated on the 647 keV γ line in ^{149}Yb. The histogram is the experimental result, while the curve stands for the statistical-model calculation with initial spin and parity of $1/2^-$.

gated on the 647 keV γ-ray was calculated using the revised statistical model, assuming the spin and parity of ^{149}Yb to be $1/2^-$. The calculated spectrum fitted the experimental data very well (see fig. 6). Finally, the ground-state spin-parity of ^{149}Yb is proposed to be $1/2^-$.

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