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Short Note

β-delayed proton decays of ^{93}Pd and ^{92}Rh

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

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

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Abstract. β-delayed proton precursors ^{93}Pd and ^{92}Rh were produced by the irradiation of ^{58}Ni with a ^{40}Ca beam, and identified using proton-gamma coincidence measurements in combination with a helium-jet fast tape transport system. The half-lives of ^{93}Pd and ^{92}Rh were determined to be 1.3(2), 3.0(8) s, respectively. The measured energy spectrum of β-delayed protons and the estimated relative branching ratios to the final states in the daughter nuclei were fitted by a statistic model calculation, and then the ground-state spin and parity of ^{93}Pd were assigned as $9/2^{\pm}$.

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 very neutron-deficient nucleus ^{93}Pd with $T_z = 1/2$ was predicted to be a probable waiting point in the astrophysical rp-process [1]. Recently, the β decay of ^{93}Pd, including β-delayed proton (βp) decay and (EC + β^+) decay, was observed by Schmidt *et al.* [2]. In order to check the shell model calculation, experimental determination of its ground-state spin and parity is necessary. The in-beam γ study of ^{92}Rh was reported and its ground state was assigned as 6^+ by Zhou *et al.* [3]. So far, the decay property of ^{92}Rh was not known yet. In this work, ^{93}Pd and ^{92}Rh were produced via the ^{58}Ni(^{40}Ca, 2p3n) and ^{58}Ni(^{40}Ca, 3p3n) fusion-evaporation reactions, respectively. In combination with a He-jet tape transport system, the proton-gamma coincidence measurements proposed in our previous studies [4–6] were employed to identify the βp precursors. Namely, the γ transitions between the low-lying states in the daughter nucleus ^{92}Ru (^{91}Tc) in coincidence with βp were used to identify the precursor ^{93}Pd (^{92}Rh).

The experiment described here was carried out at the Sector-Focusing Cyclotron in the Institute of Modern Physics, Lanzhou, China. A 232 MeV ^{40}Ca^{12+} beam from the cyclotron entered a target chamber, passing through a 1.89 mg/cm^2 thick Havar window and 2 cm of helium gas at 1 atm, and finally bombarded a self-supported ^{58}Ni target (98% enriched) with a thickness of 2.1 mg/cm^2. The target was mounted on a copper wheel surrounded by a cooling device. The beam intensity was about 40 pnA. We used a He jet in combination with a tape transport system to move the radioactivity into a shielded counting room for p-γ_1(X)-γ_2(X)-t coincidence measurements periodically. The irradiation time, tape moving time, waiting time, and accumulation time were 2.90, 0.18, 0.02, and 2.88 s, respectively. PbCl$_2$ was used as aerosol at 430°C. Two 570 mm^2 $\times$ 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 there was a coaxial HpGe(GMX) detector for γ(X) measurements. Energy and time spectra of γ(X)-ray and proton were taken in coincidence mode.

The measured γ(X)-ray spectrum gated on 2.4–5.0 MeV protons is shown in fig. 1. The upper limit of the energy signals coming from the pile-up of positrons in the silicon detectors was tested to be 2.5 MeV. Therefore, the intense lines in fig. 1 were not the γ transitions directly from (EC + β^+) decay, but the γ transitions which follow the β-delayed proton emissions. All of the intense γ lines in fig. 1 were assigned to their βp precursors except the X-rays and the 511 keV γ-ray. Among them, the 865 keV and 991 keV γ lines were assigned to the $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions in the daughter nucleus ^{92}Ru [7] of the proton emitter ^{93}Rh produced via EC/β^+decay of ^{93}Pd. We checked the lower-energy part of the measured γ(X)-ray spectrum (with energy from 30 to 500 keV) gated on 2.5–6.4 MeV protons. No clear indication of the existence of the intense β-delayed γ lines of 239.7 and 381.7 keV directly produced via the (EC + β^+) decay of ^{93}Pd [2] could be seen. Therefore, in fig. 1 the contribution coming from a weak γ line of 864.1 keV directly produced via the (EC + β^+) decay of ^{93}Pd [2] can be ignored. The decay curve of the 865 keV γ line coincident with 2.4–5.0 MeV protons, from which the half-life of ^{93}Pd was extracted to be 1.3 ± 0.2 s, is shown in the

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

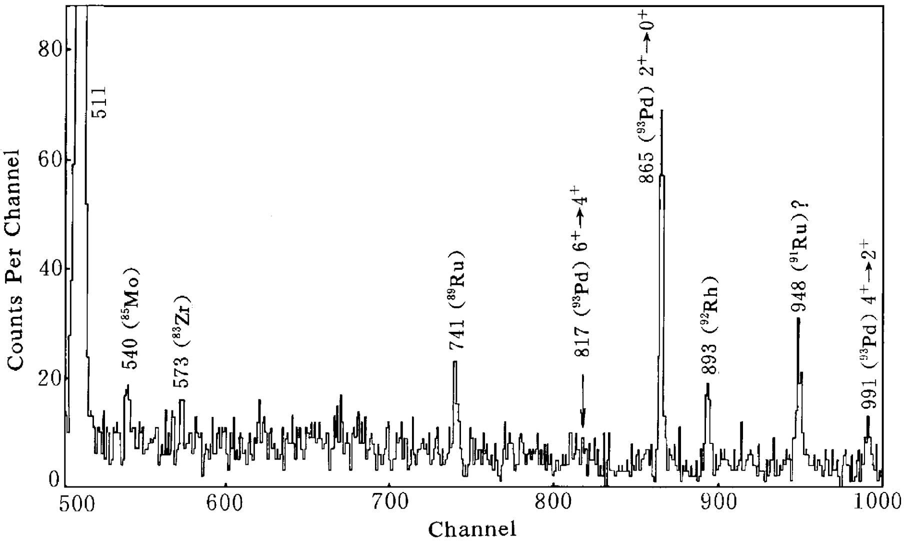

Fig. 1. The measured γ-ray spectrum in coincidence with 2.4 to 5.0 MeV protons. The intense peaks in fig. 1 are labeled with their energies in keV and their β-delayed proton precursors.

Table 1. Calculation of the relative branching ratios to different final states in the daughter nucleus ^{92}Ru and the absolute proton intensities via β-delayed proton decay of ^{93}Pd for various values of the initial spin and parity of ^{93}Pd by using the revised statistical model [10,11].

Initial spin and parity of ^{93}Pd	Relative branching ratios to the final state (%)				Absolute intensities
	G. S. (0^+)	856 keV (2^+)	1856 keV (4^+)	2673 keV (6^+)	
$1/2^-$	96.6	3.4	0.0	0.0	0.13×10^0
$1/2^+$	92.2	7.8	0.0	0.0	0.19×10^0
$3/2^-$	84.2	15.7	0.1	0.0	0.85×10^{-1}
$3/2^+$	83.2	16.7	0.0	0.0	0.15×10^0
$5/2^-$	74.8	24.8	0.4	0.0	0.59×10^{-1}
$5/2^+$	65.7	33.0	1.3	0.0	0.86×10^{-1}
$7/2^-$	49.3	47.1	3.5	0.1	0.25×10^{-1}
$7/2^+$	45.3	48.7	6.0	0.0	0.48×10^{-1}
$9/2^-$	48.6	43.2	7.9	0.3	0.15×10^{-1}
$9/2^+$	10.5	68.7	19.4	1.4	0.17×10^{-1}
$11/2^-$	9.2	61.1	26.2	3.6	0.40×10^{-2}
$11/2^+$	4.6	52.7	35.0	7.7	0.75×10^{-2}

inset of fig. 2. This result is consistent with the predicted half-life of 1.4 s calculated by Herndl and Brown [8] using a shell model calculation, and is in reasonable agreement with the previous experimental result 0.9 ± 0.2 s reported in ref. [2]. However, the measured half-life of ^{93}Pd is longer than another predicted β decay half-life: 0.22 s by Möller *et al.* [9] using a macroscopic-microscopic mass model. In fig. 1 the intensities of 865 and 991 keV γ lines, as well as the background level at 817 keV, which corresponds to the $6^+ \to 4^+$ transition in ^{92}Ru [7], were used to estimate the relative branching ratios of βp to different final states in ^{92}Ru: $100(2^+)$, $23 \pm 5(4^+)$, and $\leq 3(6^+)$. The proton energy spectrum gated on the 865 keV γ line is shown in fig. 2. The component with energy lower than 2.2 MeV in the spectrum was attributed to the pile-up of positrons in the silicon detectors. On the other hand, the energy spectrum of βp and the branching ratios of βp to different final states in ^{92}Ru were calculated with a revised statistical model [10,11]. The structureless β strength function predicted by the gross theory and the energy level density based on the back-shifted Fermi gas assumption were used in the model calculation. The Q_{EC}-value of 9.53 MeV and the B_{p} of 2.08 MeV in the calculation were taken from ref. [12]. The spins and parities of ^{93}Pd most consistent with the experimental results are $9/2^{\pm}$, which give the final-state branching ratios of βp of 43.2% and 68.7%(2^+), 7.9% and 19.4%(4^+), as well as 0.3% and 1.4%(6^+) (see table 1), and reproduce the experimental energy spectrum

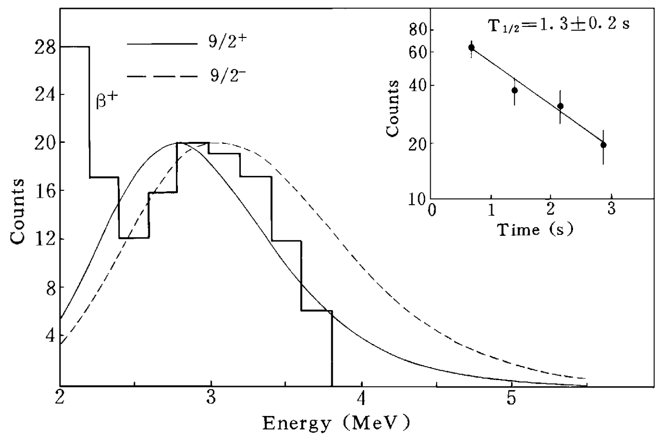

Fig. 2. Observed energy spectrum of β-delayed protons gated on the 865 keV γ-ray. The solid and dashed curves were calculated using the statistical model (see text). The inset is the decay curve of the 865 keV line coincident with 2.4–5.0 MeV protons.

of βp reasonably well (fig. 2). The assigned ground-state spins and parities of ^{93}Pd are in good agreement with the prediction of $9/2^+$ by the shell model calculation [8] and by Audi *et al.* [12] based on systematic trends. According to the simple EC/β^+decay scheme of ^{93}Pd without the branching ratio decayed to the ground state of ^{93}Rh proposed by Schmidt (fig. 3 and table 1 in ref. [2]), the upper limit of absolute intensity of 864.1 keV γ transition in ^{93}Rh per ^{93}Pd decay was estimated to be 9 $\pm$ 2%. On the other hand, assuming the ground-state spin and parity of ^{93}Pd as $9/2^+$, the absolute intensity of the β-delayed proton decay of ^{93}Pd was calculated to be 1.7% by using the statistical model (see table 1). Finally, the total branching ratio leading to the 865 keV γ transition from the lowest-energy 2^+ state to the 0^+ ground state in ^{92}Ru, following the proton emission in the β-delayed proton decay of ^{93}Pd, was estimated to be 1.5%. Therefore, the 864.1 keV β-delayed γ transition in the EC/β^+ decay of ^{93}Pd reported in ref. [2] might be the 865 keV γ transition following the β-delayed proton decay of ^{93}Pd observed in this work.

According to the in-beam study of ^{91}Tc [13], the 893 keV γ line in fig. 1 was assigned to the $13/2^+ \to 9/2^+$ transition in the daughter nucleus ^{91}Tc of the proton emitter ^{92}Ru produced via EC/β^+decay of ^{92}Rh. The intense $13/2^+ \to 9/2^+$ transition indicates that the ground-state spin of ^{92}Rh should be equal to or larger than 5. This conclusion is consistent with the previous experimental result of 6^+ reported in ref. [3], however is contradicted by the shell model prediction of 2^+ [8]. The βp energy spectrum of ^{92}Rh gated on the 893 keV γ line is shown in fig. 3. The component with energy lower than 2.2 MeV in the spectrum was attributed to the pile-up of positrons in the silicon detectors. The decay curve of the 893 keV γ line coincident with 2.4–5.0 MeV protons, from which the half-life of ^{92}Rh was extracted to be 3.0 ± 0.8 s, is shown in the inset of fig. 3. The extracted half-life is in reasonable agreement with the prediction of 4.3 s reported in ref. [8], however, is longer than the predicted β decay half-lives: 1.1 s by Horiguchi *et al.* [14] using the gross theory and 0.35 s by Möller *et al.* [9].

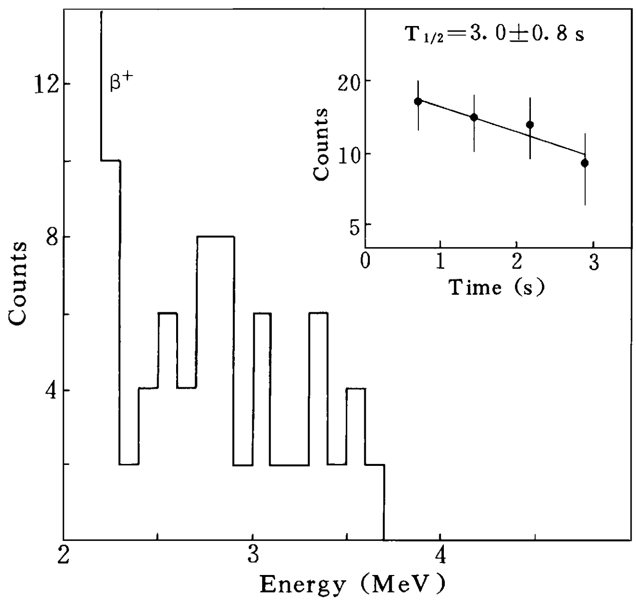

Fig. 3. Observed energy spectrum of β-delayed protons gated on the 893 keV γ-ray. The inset is the decay curve of the 893 keV line coincident with 2.4–5.0 MeV protons.

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