β-delayed proton decays of the $T_z=1/2$ series nuclei, ^{81}Zr and ^{85}Mo

W. X. Huang, R. C. Ma, S. W. Xu, X. J. Xu, J. S. Guo, X. F. Sun, Y. X. Xie, Z. K. Li, Y. X. Ge, Y. Y. Wang, C. F. Wang, T. M. Zhang, G. M. Jin, and Y. X. Luo
Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
(Received 14 April 1998)

The decays of $T_z=1/2$ series nuclei ^{81}Zr and ^{85}Mo have been restudied via their β-delayed proton decay by using p-γ coincidence measurements. The β-delayed proton spectra populating the first excited states of the final nuclei have been obtained. By using statistical model calculations with level densities calculated with a backshifted Fermi gas model, the spin and parity for the ground state of ^{81}Zr have been tentatively assigned to be $3/2^-$ and those for ^{85}Mo to be $1/2^-$. Their $Q_{\rm e.c.}-B_p$ values are 4.7 ± 0.2 and 5.1 ± 0.2 MeV, which correspond to mass excesses of -58.3 ± 0.2 MeV for ^{81}Zr and of -59.1 ± 0.4 MeV for ^{85}Mo, respectively. Combining the measured half-lives with the calculated partial ones yields branches of β-delayed proton decay for ^{81}Zr and ^{85}Mo of $(1.2\pm0.2)\times10^{-3}$ and $(1.4\pm0.2)\times10^{-3}$, respectively. [S0556-2813(99)02703-X]

PACS number(s): 21.10.Hw, 23.40.Hc, 27.50.+e, 23.50.+z

β-delayed proton decay is one of the important and characteristic decay modes of very proton-rich nuclei [1]. The unique signature of the β-delayed proton emission allows these nuclei to be detected even though they are in a very high β background arising from nuclides which lie closer to the valley of stability. In the light mass region, delayed proton spectra are composed of discrete transitions from levels in the β decay daughter (emitter) to levels in the final nucleus (daughter), usually dominated by transitions from the isobaric analog state (IAS) [2–6], because levels in the emitter typically have spacings larger than the proton detector resolution due to the relatively low level density. In contrast, in the heavier mass region, because of a lack of the IAS and the relatively high level density, the delayed proton spectra appear as board bell-shape continuum [7–10]. In this region, the β-delayed proton spectra can be most readily analyzed by statistical methods. Such an analysis can provide information on the decay energy, the spin and parity of the precursor, and other information which is difficult to obtain by other methods for these far-unstable nuclei.

We present here our new results for the two β-delayed proton precursors ^{81}Zr and ^{85}Mo, which have the same $T_z=1/2$. Some other nuclides of this series, ^{65}Ge [8], ^{69}Se [7,8], ^{73}Kr [8,11], ^{77}Sr [8], ^{97}Cd [12], and ^{101}Sn [13], have been reported as β-delayed proton precursors. ^{81}Zr was studied [14,15] via its β-delayed proton decay and a half-life was measured to be 5.9 ± 0.6 s. Its spin and parity were assigned to be $3/2^-$ [16]. It was restudied [17] by β-recoil time-of-flight mass spectrometer and a much longer half-life of 15 ± 5 s was reported. ^{85}Mo was only studied by Hardy *et al.* [14] and a half-life of 5.6 s was reported. Their half-life values measured in our experiment have been reported in [18].

It is very interesting to study the characteristic of a nuclide with the same proton and neutron number. ^{81}Zr and ^{85}Mo are only one neutron more than the self-conjugation nuclei ^{80}Zr and ^{84}Mo. Additionally, they are in the region of rapidly changing deformation. Nuclides close to the center of the $28<Z,N<50$ shell are known [19] to be strongly deformed.

In β^+ [including electron capture (e.c.)] decay of a precursor, excited states above the proton binding energy in the emitter could be populated, which will deexcite to the ground or low-lying states of the daughter. For example, ^{81}Zr may decay via the following path:

$$^{81}\mathrm{Zr}\xrightarrow{\beta^+/\mathrm{e.c.}}{}^{81}\mathrm{Y}\xrightarrow{p}{}^{80}\mathrm{Sr}(2^+)\xrightarrow{\gamma 386}{}^{80}\mathrm{Sr}(0^+),$$

and in the case of ^{85}Mo, the path can be written

$$^{85}\mathrm{Mo}\xrightarrow{\beta^+/\mathrm{e.c.}}{}^{85}\mathrm{Nb}\xrightarrow{p}{}^{84}\mathrm{Zr}(2^+)\xrightarrow{\gamma 540}{}^{84}\mathrm{Zr}(0^+),$$

and so one can identify ^{81}Zr and ^{85}Mo via p-386-keV-γ and p-540-keV-γ coincidence measurements, respectively. This method has been confirmed by the identification of a new nuclide ^{135}Gd [20].

The experiment was performed at HIRFL (Heavy Ion Research Facility in Lanzhou). A He-jet technique in combination with a tape-transport system was employed in the experiment. The main part of the setup is shown schematically in Fig. 1. A 170-MeV $^{32}S^{9+}$ beam with an average current of 0.3e μA was directed onto an enriched isotopic ^{58}Ni target with a thickness of 3.0 mg/cm^2 which was cooled by flowing water. The effect of the beam energy on the target was 150 MeV due to losing energy in the entrance window (Harvar foil of 1.94 mg/cm^2) and the helium gas. The products were thermalized by helium in the target chamber and attached on NaCl clusters which was used for increasing the transport efficiency. They were rapidly transported to the collection chamber through a 15-m-long capillary and implanted onto a metallic tape. The tape was moved periodically and the radioactive sample was carried to an array of detectors. The moving periods used in this experiment were 3 s and 13 s. When a sample was being measured, another one was being cumulated.

Protons were detected in a 300 mm$^2\times300$ μm Si(Au) surface barrier detector, right behind which a 300 mm^2 $\times400$ μm Si(Au) surface barrier detector was also used for anticoincidence measurements in order to reduce β^+ pileup.

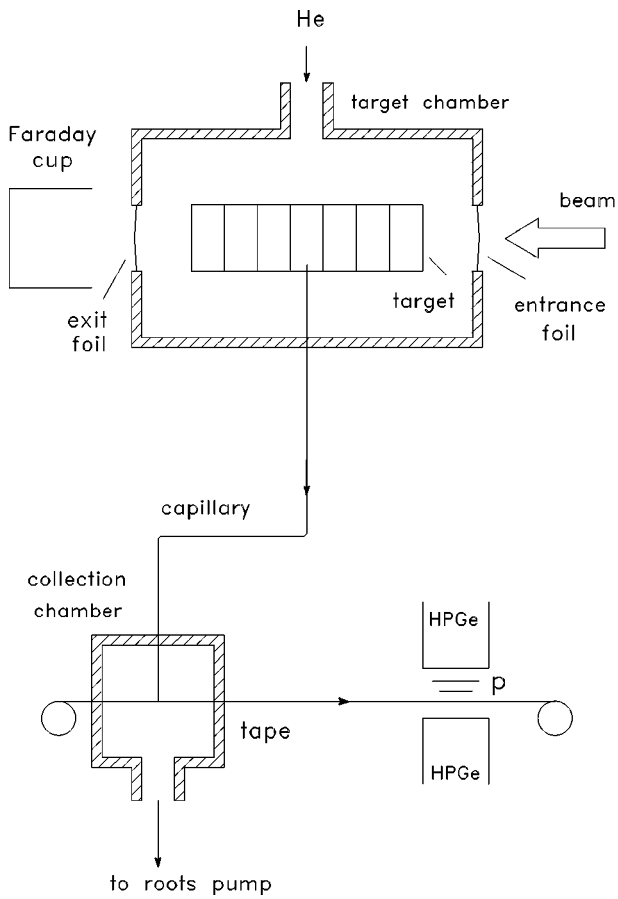

FIG. 1. Schematic diagram of the main part of the experimental setup.

This system has a solid angle of 40%$\times 4\pi$ sr and the energy resolution was 60 keV full width at half maximum (FWHM) for 5.486 MeV ^{241}Am alphas. Gamma rays were detected by two coaxial HPGe detectors of which one was placed immediately behind the Si(Au) detectors and the other was placed opposite the Si(Au) detectors. A ^{241}Am alpha source was used to calibrate the Si(Au) detectors and a precision pulser to establish linear energy response. Standard gamma sources of ^{137}Ba and ^{152}Eu were used to calibrate the energy and efficiency of the HPGe detectors.

Coincidences between protons and γ rays were recorded event by event on magnetic tapes for subsequent off-line analysis. After the arrival of a fresh sample of isotopes at the detector array a quartz-controlled clock was started that tagged all events with a relative time signal for half-life information, which was recorded on magnetic tape simultaneously.

Figure 2 is the gamma spectrum gated by protons. Figure 3 (a) shows the proton spectrum gated by the 386-keV γ rays. It is the β-delayed proton spectrum of ^{81}Zr populating the first excited state of ^{80}Sr. The time spectrum of the 386-keV γ rays gated by protons is shown in Fig. 3(b). Figure 4(a) shows the β-delayed proton spectrum of ^{85}Mo populating the first excited state in ^{84}Zr gated by the 540-keV γ rays. The time spectrum of the 540-keV γ rays gated by protons is also shown in Fig. 4 (b).

The statistical-model technique used here is described in detail in an article by MacDonald *et al.* [7]. Some parts of

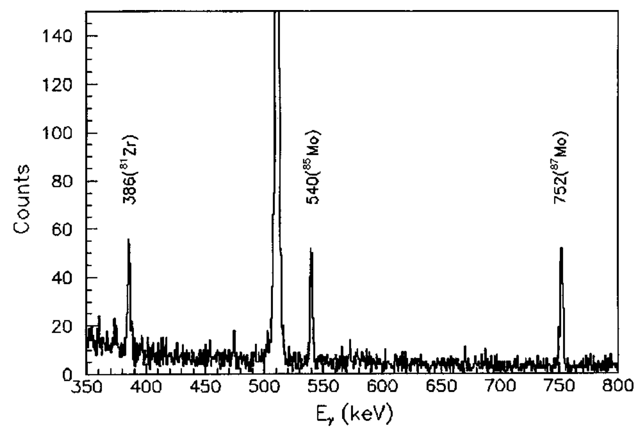

FIG. 2. The gamma spectrum gated by protons.

the theoretical quantities used in the analysis have been improved [11,21]. The technique can perform the β-delayed proton decay not only to the ground state but also to the first excited state of the daughter so we can use the theoretical results of the latter part to fit our proton spectrum. Because of poor statistics in Fig. 3(a) and Fig. 4(a), we ignore the fluctuations caused by a Porter-Thomas distribution [22] and concentrate on describing the general features of the spectrum.

Except for the following mentioned variables, others follow those in Refs. [7,11,21]. The first one is the level density. The level densities calculated with the formulas of Gilbert and Cameron [23] and with the backshifted Fermi gas model [24] have been considered. In Ref. [21], Hardy calculated the average radiation widths $\langle\Gamma_\gamma\rangle$ by using the two kinds of level density and pointed out that excellent results

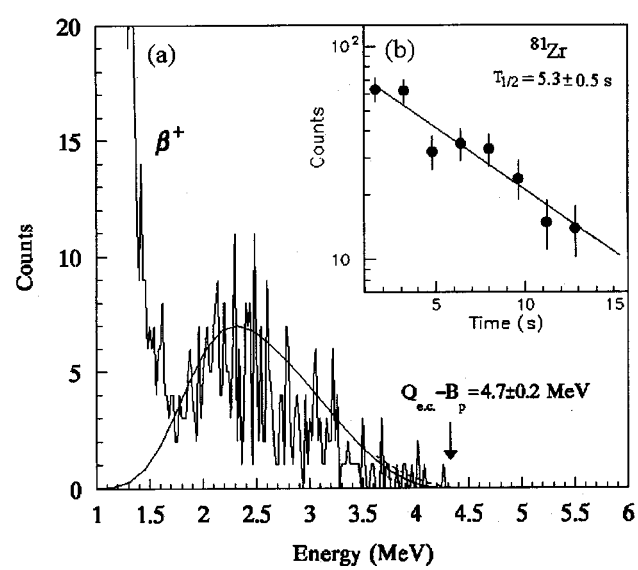

FIG. 3. (a) The energy spectrum of protons gated by the 386-keV γ ray, which is the β-delayed proton spectrum of ^{81}Zr populating the first excited state in ^{80}Sr. The solid curve is the calculated spectrum shape obtained from statistical-model calculations assuming a $Q_{\mathrm{e.c.}}-B_p$ value of 4.7 MeV and a spin and parity of $3/2^-$. The dashed curves on either side of the solid curve are the predicted shapes for $Q_{\mathrm{e.c.}}-B_p$ values 200 keV larger and smaller than 4.7 MeV. The arrow indicates the end point for the best fit. See text. (b) The time spectrum of the 386-keV γ ray gated by protons.

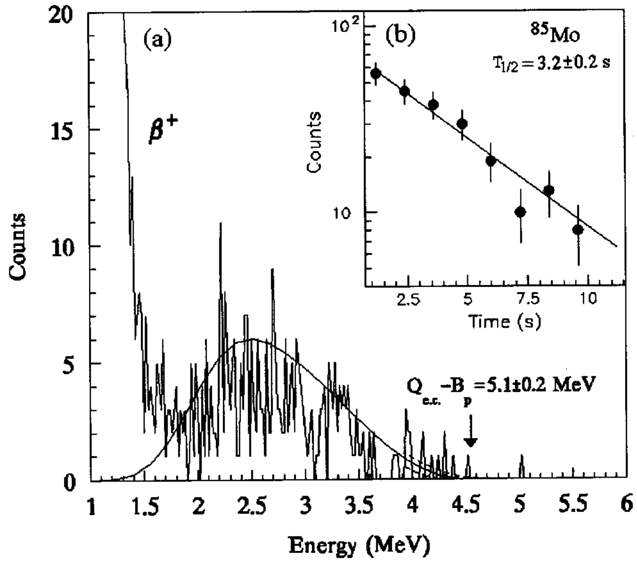

FIG. 4. (a) The energy spectrum of protons gated by the 540-keV γ ray, which is the β-delayed proton spectrum of ^{85}Mo populating the first excited state in ^{84}Zr. The predicted spectrum shape for a $Q_{\text{e.c.}}-B_p$ value of 5.1 MeV and a spin and parity of $1/2^-$ is shown as the solid line, whereas the two dashed lines represent the predictions for $Q_{\text{e.c.}}-B_p$, 4.9 MeV and 5.3 MeV, respectively. The arrow indicates the end point for the best fit. See text. (b) The time spectrum of the 540-keV γ ray gated by protons.

were obtained if level densities were calculated with the backshifted Fermi gas model but not if Gilbert-Cameron densities were used; so we use the level densities calculated with the backshifted Fermi gas model. In our computation we have assumed that the energies of fictive ground states are both -0.3 MeV for ^{81}Zr and ^{85}Mo, because the values are between 0.0 and -0.6 MeV for $80<A<90$ [24], and the level density parameter $a=12$, because we lack such values for ^{81}Zr and ^{85}Mo and the surveys in Ref. [25] exhibit a range between 10 and 15 MeV^{-1} for $A\approx 80$.

The other variables are the decay energy and the spins and parities of the initial and final states. The total proton decay energy mainly affects the shape of the high-energy tail of the proton spectrum, and the spins and parities of the states involved in the decay mainly influence the shape of the whole proton spectrum and the magnitude of the proton branches feeding excited states in the final nuclide. In our cases, spins and parities of 0^+ have been used for the daughters ^{80}Sr and ^{84}Zr because they are even-even nuclei and $5/2^+$ and $9/2^+$ for the emitters ^{81}Y and ^{85}Nb, respectively [26]. By fitting the shape of the proton spectrum, we can obtain the decay energy and the spin and parity of the precursor. Indeed, the decay energy can also be deduced by the fraction of delayed protons emitted after β^+ decay (from coincidences with annihilation radiation), but in our experiment, all protons from various nuclei are mixed into one and we could not distinguish the protons for a special nuclide from the total spectrum and the protons populating the ground state of the daughter for a special nuclide as well; so we have to neglect this method to deduce the decay energy.

The mass of precursor can be obtained by combining the mass of the daughter with the $Q_{\text{e.c.}}-B_p$ value where $Q_{\text{e.c.}}$ is the beta-decay energy of the precursor and B_p the proton separation energy of the emitter. This value can be determined from a fit to the high-energy tail of the delayed proton spectrum.

The calculated results of statistical model are shown in Fig. 3(a) and Fig. 4(a) as fully drawn curves for the β-delayed proton spectra of ^{81}Zr and ^{85}Mo, respectively. The basic properties of ^{81}Zr and ^{85}Mo are listed in Table I.

For the ^{81}Zr case, a $Q_{\text{e.c.}}-B_p$ value of 4.7 MeV with an uncertainty of 0.2 MeV has been obtained from the best fit with the experimental data. Combining the mass excess of ^{80}Sr [27] of -70.302 ± 0.008 MeV with our measured $Q_{\text{e.c.}}-B_p$ value, the mass excess of ^{81}Zr is deduced to be -58.3 ± 0.2 MeV, which is in agreement with the systematical value -58.9 ± 0.3 MeV [27]. In the computation many spins and parities fit the experimental proton spectrum well, maybe because of poor statistics. Sahu and Pandya [28] have calculated the spectra likely to be obtained in ^{81}Zr and noted that the ground state of ^{81}Zr may have the spin and parity of either of $(1/2, 5/2, 3/2)^-$ or $(3/2,5/2)^+$. Considering the above information and the ratio of $(24\pm8)\%$ of β-delayed protons feeding the first excited state of ^{80}Sr [16], we tentatively assign the spin and parity of $3/2^-$ to the ground state of ^{81}Zr, which is in agreement with the previous assigned one [16]. In Fig. 3(a) we present the calculated result by assuming the spin and parity of $3/2^-$. We could not compare it with all other $N=41$ isotones because they show very poor systematics. Combining the experimental half-life of 5.3 ± 0.5 s [18] with the calculated partial one for proton

TABLE I. The basic properties of ^{81}Zr and ^{85}Mo.

	This work				Previous work		
	$T_{1/2}$ (s)	ΔM (MeV)	J^π	Proton-decay branching	$T_{1/2}$ (s)	J^π	ΔM (MeV)
^{81}Zr	5.3 ± 0.5	-58.3 ± 0.2 [a]	$3/2^-$	$(1.2\pm0.2)\times10^{-3}$	5.9 ± 0.6 [c], 15 ± 5 [d]	$3/2^-$ [e]	-58.9 ± 0.3 [f]
^{85}Mo	3.2 ± 0.2	-59.1 ± 0.4 [b]	$1/2^-$	$(1.4\pm0.2)\times10^{-3}$	5.6 [c]		-59.1 ± 0.4 [f]

[a]This value was given by combining the experimental mass excess of ^{80}Sr [27], -70.302 ± 0.008 MeV, with our measured $Q_{\text{e.c.}}-B_p$ value 4.7 ± 0.2 MeV.
[b]As above, but using the systematical mass excess of ^{84}Zr [27], -71.49 ± 0.30 MeV and our measured $Q_{\text{e.c.}}-B_p$ value 5.1 ± 0.2 MeV.
[c]Reference [14].
[d]Reference [17].
[e]Reference [16].
[f]Reference [27].

decay, a β-decay branching ratio to the proton emitting states was obtained to be $(1.2\pm0.2)\times10^{-3}$.

The best fit with the ^{85}Mo data yields a $Q_{\mathrm{e.c.}}-B_p$ value of 5.1 ± 0.2 MeV. Combining the systematical value of mass excess of ^{84}Zr [27], -71.49 ± 0.30 MeV, with our $Q_{\mathrm{e.c.}}-B_p$ value, the mass excess of ^{85}Mo is then deduced to be -59.1 ± 0.4 MeV, which equals the systematical value [27]. As in the case for ^{81}Zr, we assume spin and parity of the precursor to be either of $(1/2, 3/2, 5/2)^-$ or $(5/2,7/2)^+$ and fit the proton spectrum well. Because we could not extract the ratio of β-delayed protons populating the first excited state of ^{84}Zr and have not measured x rays emitted from nuclei, we could not restrict the analysis. But the ground states of all other $N=43$ isotones have a spin and parity of $1/2^-$, and a $7/2^+$ isomeric state is always present; so we tentatively assign the spin and parity of $1/2^-$ to the ground state of ^{85}Mo, which gives the reasonable ratio of $\sim10\%$ of β-delayed protons feeding the first excited state of ^{84}Zr in the calculation. In Fig. 4(a) we present the calculated result by assuming the spin and parity of $1/2^-$. Combining the experimental half-life of 3.2 ± 0.2 s [18] with the calculated partial one for proton decay, a β-decay branching ratio to the proton emitting states for ^{85}Mo decay was deduced to be $(1.4\pm0.2)\times10^{-3}$.

In conclusion, we have reinvestigated the β-delayed proton decays of ^{81}Zr and ^{85}Mo. They both belong to the nuclear series $T_z=1/2$. By using a proton-γ coincidence measurement technique, the β-delayed proton spectra populating the first excited states of the final nuclides have been obtained. And by using statistical model calculations and systematical analyses we have obtained the following results.

For ^{81}Zr, a half-life of 5.3 ± 0.5 s has been unambiguously obtained which is in agreement with one of the two previous values of 5.9 ± 0.6 s [14]. Its mass excess has been measured to be -58.3 ± 0.2 MeV. A spin and parity of $3/2^-$ has been tentatively assigned to the ground state of ^{81}Zr. Additionally, a branching ratio of β-delayed proton decay has been obtained to be $(1.2\pm0.2)\times10^{-3}$.

For ^{85}Mo, a half-life of 3.2 ± 0.2 s has been determined which revises the previous value of 5.6 s [14] and a mass excess of -59.1 ± 0.4 MeV has been given. A spin and parity of $1/2^-$ have been tentatively assigned to the ground state and a branching ratio of β-delayed proton decay has been deduced to be $(1.4\pm0.2)\times10^{-3}$.

One of the authors (W.X.H.) thanks Prof. Yongtai Zhu for his help with the target. This work was supported financially by the Chinese Academy of Sciences and the National Natural Science Foundation of China (Grant No. 19805011).

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