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Short Note

New β-delayed proton precursor ^{149}Yb near the proton drip line

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Abstract. The β-delayed proton precursor ^{149}Yb was synthesized in the reaction ^{112}Sn(^{40}Ca, 3n) and identified by using a proton-gamma coincidence measurements in combination with a helium-jet fast tape transport system. Its β-delayed proton spectrum was observed. The half-life of ^{149}Yb was determined to be 0.7 ± 0.2 s. The 253, 101, and 365 keV γ transitions in ^{147}Dy, following β-delayed proton emission of ^{148}Ho decay, were reported 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 very neutron-deficient heavy rare-earth nuclide ^{149}Yb has been predicted to be a β-delayed proton precursor along the proton drip line $Z = 0.743 \times N + 11.6$ speculated by Hofmann [1]. Study of its β-delayed proton decay is of interest. ^{149}Yb was produced via the ^{112}Sn(^{40}Ca, 3n) fusion-evaporation reaction. The partial reaction cross-section for production and decay via β-delayed proton channel of ^{149}Yb was quite low. In combination with a He-jet tape transport system, the proton-gamma coincidence with higher sensitivity of measurements proposed in our previous study [2–4] was employed to identify the β-delayed proton precursor. Namely, the γ transitions between the low-lying states in the daughter nucleus ^{148}Er in coincidence with β-delayed protons were used to identify the precursor ^{149}Yb.

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 filled with 1 atm helium, passing through a 1.89 mg/cm^2 thick Havar window and 6 cm helium gas, and finally bombarded with, in turn, four self-supported ^{112}Sn targets (94% 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 90° once every 2.5 minutes. The beam intensity was about 0.5 eμA. 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 collection time, tape moving time, waiting time, and accumulation time were 1.20, 0.18, 0.02, and 1.18 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 2.5–6.4 MeV protons is shown in fig. 1. All of the intense γ lines in fig. 1 were assigned to their β-delayed proton precursors except the X-rays and 511 keV γ-ray. No clear peak could be seen at the energies of 877 keV and 1003 keV, which correspond to the $4^+ \to 2^+$ and $6^+ \to 4^+\gamma$ transitions in ^{148}Er [5] produced via the EC/β^+ decay of ^{148}Tm, respectively. The efficiency of the γ detector we used at 1.0 MeV is about 20% less than that at 647 keV. Therefore, the contribution of β-delayed 647 keV γ transition from the lowest-energy 2^+ state to the 0^+ground state in the daughter nucleus ^{148}Er [5] could be ignored, and the 647 keV γ line was assigned to the transition from the lowest-energy 2^+ state to the 0^+ground state in the daughter nucleus ^{148}Er of the proton emitter ^{149}Tm produced via the EC/β^+ decay of ^{149}Yb. Following the in-beam studies of ^{147}Tb [6], the 253, 101 and 365 keV γ-rays were assigned for the first time to the decay of β-delayed proton precursor ^{148}Ho. They correspond to the transitions of $3/2^+ \to 1/2^+$, $5/2^+ \to 3/2^+$, and $7/2^+ \to 5/2^+$ in ^{147}Tb, respectively. Taking the efficiency of γ detector and the internal-conversion coefficient into account, the relative intensities for the three transitions are 100 ± 15, 105 ± 30, and 45 ± 10, respectively.

The measured γ(X)-ray spectrum gated on 0.3 to 2.5 MeV signals of the two silicon detectors is shown in

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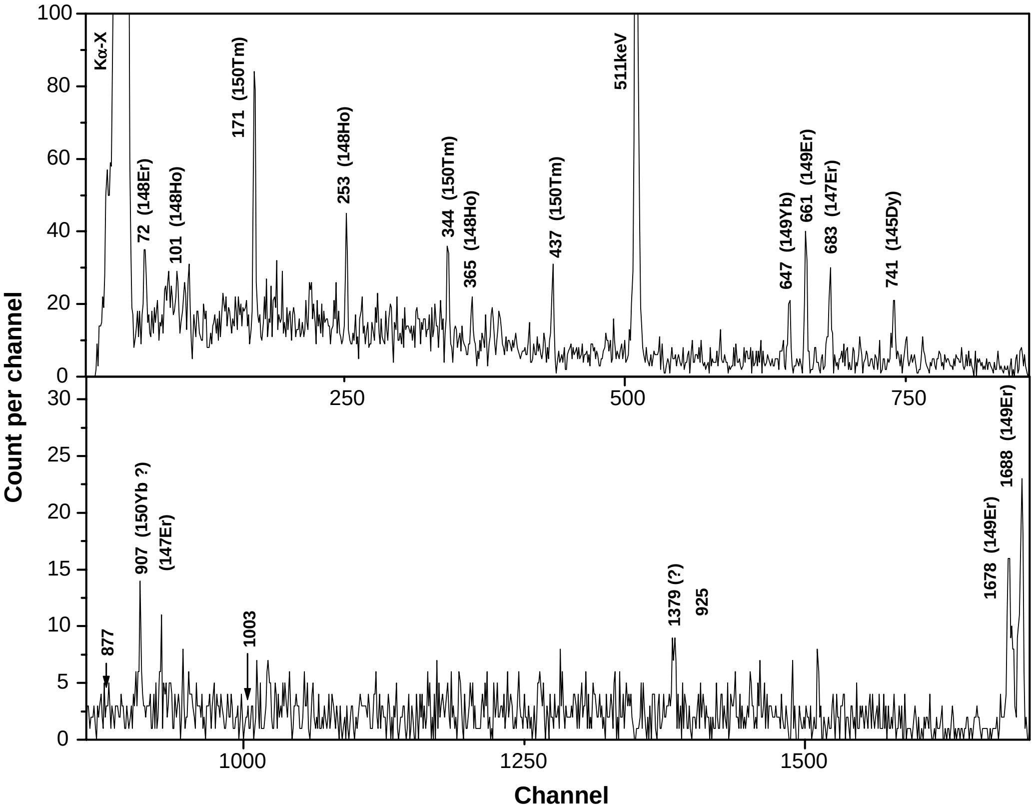

Fig. 1. Measured γ-ray spectrum in coincidence with 2.5 to 6.4 MeV protons. The intense peaks are labeled with their energies in keV and their β-delayed proton precursors.

fig. 2. It is mainly a distorted β^+-delayed γ spectrum. Although several intense γ lines have not been assigned definitely, the following intense pure β^+-delayed γ lines with negligible component from β-delayed proton decay can be seen in fig. 2: 1) The 1579, 208, and 475 keV lines are pure β^+-delayed γ from ^{150}Tm [7]. They are not from the β-delayed proton decay of ^{151}Yb because the precursor ^{151}Yb was not able to be produced in the ^{40}Ca + ^{112}Sn reaction. 2) The 884, 190, and 487 keV lines are pure β^+-delayed γ from^{147}Ho [8], and correspond to $5/2^+ \rightarrow 3/2^+$, $7/2^- \rightarrow 5/2^+$, and $9/2^- \rightarrow 7/2^-$ transitions in ^{147}Dy [8]. The probability of the β-delayed proton decay from the 0^+ ground state of even-even precursor ^{148}Er leading to the final states with spin $\geq 5/2$ in ^{147}Dy is very small. 3) The 1171 keV line is a pure β^+-delayed γ from ^{149}Er [9] which was not reported in the previous study of β-delayed proton decay of ^{150}Tm [10]. It should be noted that all above seven pure β^+-delayed γ lines almost disappear in fig. 1. In addition, only one signal or two with energy larger than 2.5 MeV is shown in fig. 3 which is the spectrum of silicon-detector signals gated on the 1579 keV pure β^+-delayed γ line. These facts indicate that 2.5 MeV is a reasonable threshold to separate the pile-up signals of positions from the signals of protons in silicon detectors. In fig. 1 the energies of the four new γ lines that we assigned to the β-delayed proton decays are 647, 253, 101, and 365 keV, respectively. None of the four energies is a sum of the energies of any other two intense γ lines in fig. 1. Furthermore, we could not see any clear γ peaks at the same energies in fig. 2. Therefore, we believe that the four assigned γ lines are really from β-delayed proton decays rather than any other accidental causes, such as trivial summing or pile-up effects.

The proton energy spectrum gated on the 647 keV γ line is shown in fig. 4, which is the spectrum of the β-delayed proton from the ^{149}Yb decay followed by the 647 keV transition in ^{148}Er. The component with the energy lower than 2.4 MeV in the spectrum was attributed to the pile-up of positrons in the silicon detectors. The decay curve of the 647 keV γ line coincident with 2.5–6.4 MeV protons is shown in the inset of fig. 4, from which the half-life of ^{149}Yb was extracted to be 0.7 ± 0.2 s. The result is consistent with the predicted half-life of 0.6 s given by Audi *et al.* [11] based on systematic trends, and in reasonable agreement with the predicted β-decay half-life of ^{149}Yb, 0.75 s by Horiguchi *et al.* [12] using the Gross theory. However, the measured half-life of ^{149}Yb is longer than the other predicted β-decay half-life, 0.30 s given by Möller *et al.* [13] using the macroscopic-microscopic mass model.

The experimental counting rate of the 647 keV γ-ray in coincidence with 2.5–6.4 MeV protons was ~ 1.5 counts/h. Based on a revised statistical model calculation [14], assuming the ground-state spin and parity of ^{149}Yb were $1/2^+$ and $1/2^-$, the β-delayed proton branching ratios to the 0^+ ground state of the daughter nucleus ^{148}Er were

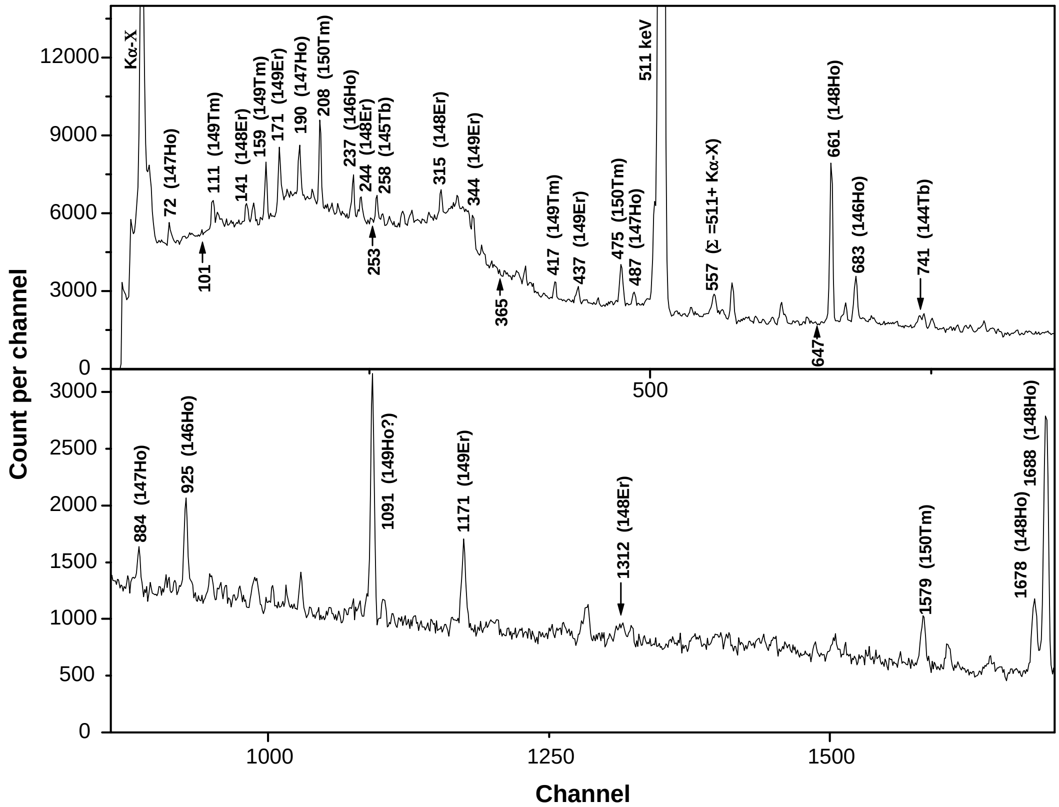

Fig. 2. Measured γ-ray spectrum in coincidence with 0.3 to 2.5 MeV signals of the silicon detector. The intense peaks are labeled with their energies in keV and their β-delayed gamma precursors.

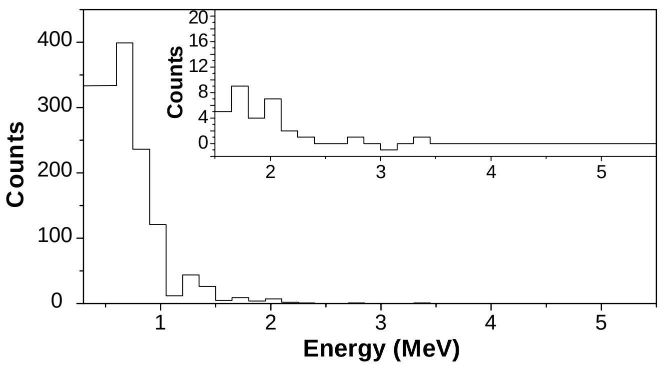

Fig. 3. Energy spectrum of silicon-detector signals gated on the 1579 keV pure β^+-delayed γ line. The inset is a close view of the spectrum with energies larger than 1.5 MeV.

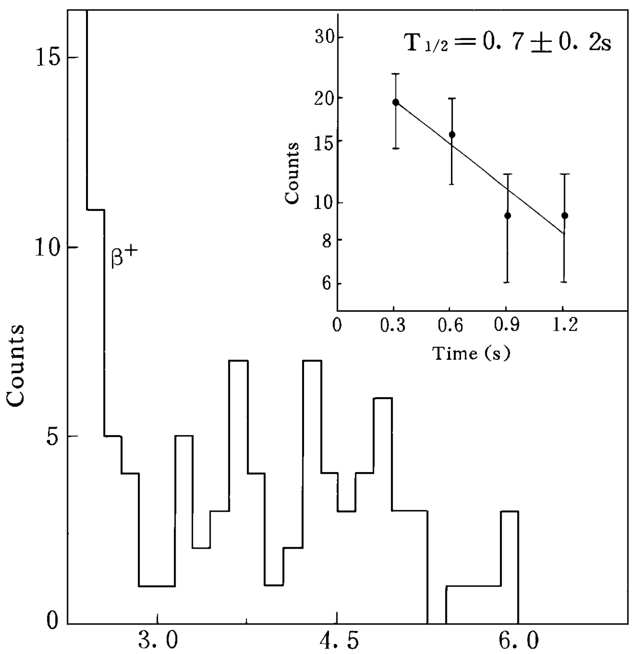

Fig. 4. Observed energy spectrum of β -delayed protons gated by the 647 keV γ-ray. The inset is the decay curve of the 647 keV γ line coincident with 2.5–6.4 MeV protons.

estimated to be 78% and 75%, respectively. In other words, the lower limit of the total branching ratio of β-delayed protons followed by the 647 keV γ-ray in ^{149}Yb decay is about 25%. If the total branching ratio of β-delayed protons followed by the 647 keV γ-ray in ^{149}Yb decay was assumed to be 50% with the uncertainty of a factor of 2, the average partial cross-section for production and decay via β-delayed proton channel of ^{149}Yb was roughly estimated to be 0.2 μb.

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