Identification of the new isotope ^{224}Np

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The new isotope ^{224}Np was produced in the fusion-evaporation reaction of ^{40}Ar + ^{187}Re and identified through the evaporation residue (ER)–α-decay correlation measurements using the digital pulse processing technique. Two α-decay branches with α energies of 9137(20) and 8868(62) keV were assigned to ^{224}Np, decaying to two excited states in ^{220}Pa. The half-life of ^{224}Np was deduced to be 38^{+26}_{-11} μs.

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I. INTRODUCTION

Investigation of the decay properties of unknown nuclei is an intrinsic interest in nuclear physics, especially for those far from the β stability line. Such decay data can be used to estimate their ground-state masses and configurations for establishing the systematic trends in ground-state properties. It has been over 20 years since the discovery of the heaviest and most neutron-deficient $N = 131$ isotone ^{223}U [1]. On one hand, it is due to the fact that the half-lives for the α-decay daughters ($N = 129$) of the $N = 131$ isotones are very short ($\sim$1 μs) and the signal pileup in the decay chain is hardly resolved by conventional analog electronics. On the other hand, the cross sections to synthesize these nuclei by heavy-ion-induced fusion reactions are rather small, because fission of the compound nucleus becomes the dominant channel [2].

Recently, we successfully applied the modern digital pulse processing (DPP) technique [3,4] to the decay spectroscopy of ^{223}Np and ^{220}Pa [5,6]. In this paper, we report on the observation of a new neptunium isotope ^{224}Np using this method.

II. EXPERIMENT

The isotope ^{224}Np was produced in the fusion-evaporation reaction of ^{40}Ar + ^{187}Re by evaporating 3n from the excited compound nucleus ^{227}Np*. A beam of 188-MeV ^{40}Ar ions provided by the Sector-Focusing Cyclotron (SFC) of the Heavy Ion Research Facility in Lanzhou (HIRFL) bombarded an isotopically enriched 460-μg/cm^2 ^{187}Re target with an average beam intensity of 320 pnA for a period of $\sim$110 h. After they were separated and transported by the gas-filled recoil separator, Spectrometer for Heavy Atoms and Nuclear Structure (SHANS) [7], the evaporation residues (ERs) passed through a multiwire proportional counter (MWPC) and then implanted into a 300-μm double-sided silicon strip detector (DSSD), with 48 horizontal and 128 vertical strips 1 mm wide. The MWPC was used for distinguishing the radioactive α decay of implanted ERs from beam-related events. In order to provide veto signals for energetic light particles passing through the DSSD, three 300-μm silicon detectors, each with an active area of 50×50 mm^2, were installed side by side behind the DSSD. Preamplifiers with rise time of $\sim$40 ns were used to resolve fast decay signals following the implantation of ERs and were equipped very close to the silicon detectors. All the silicon detectors and the preamplifiers were operated at a low temperature by using an alcohol cooling system.

The digital electronics used in the present experiment were 27 14-bit flash analog to digital converters (ADCs) from CAEN [8]. The wave forms of the signals from all preamplifiers were independently recorded in 15-μs-long traces with an effective sampling rate of 50 MHz. For the overlapping signals, different algorithms were applied in the extraction of the energies of individual signals depending on the time difference ΔT between them [5,6].

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TABLE I. The decay chains assigned to ^{224}Np in the present work. The units are keV for the implantation energy of ER and the α particle energies. The errors of the α energies are estimated using the energy resolution of DSSD [5].

Event no.	E_{ER}	$E_{\alpha 1st}$ (^{224}Np)	$E_{\alpha 2nd}$ (^{220}Pa)	$E_{\alpha 3rd}$ (^{216}Ac)	$\Delta T_{\alpha 1st}/\mu$s	$\Delta T_{\alpha 2nd}$/ns	$\Delta T_{\alpha 3rd}/\mu$s
1	12566	9144(23)	9522(45)	9058(9)	0.66	580	310.78
2	14138	9154(23)	9587(23)	1912(9)	160.71	680	600.43
3	13704	9144(60)	9531(60)		24.07	220	
4	13233	9104(60)	644(60)	9082(9)	68.93	240	166.08
5	12579	479(30)	9572(30)	8976(9)	70.81	500	527.34
6	13144	8868(60)	9811(60)	9067(9)	4.89	100	431.74

Two reactions ^{40}Ar + ^{175}Lu and ^{40}Ar + ^{186}W were used at the same beam energy to calibrate the DSSD by using the well-known α radioactivities of ERs. For non-pileup events, the energy resolution of the DSSD was 22 keV (FWHM). When the ΔT of the overlapping signals decrease to ~0.5 and ~0.2 μs, the energy resolution are around 55 and 70 keV, respectively. Details of the experiment were described in Refs. [5,6].

III. RESULTS

New isotope ^{224}Np can be identified by establishing its α decay sequences, up to the α decay of ^{220}Pa or ^{216}Ac [6,9–11], as ^{212}Fr ($b_\alpha \approx 43\%$), the daughter of ^{216}Ac, has a half-life of 20.0(6) min [11], too long to be correlated in this experiment. Six correlated decay chains were assigned to ^{224}Np in the present work and are listed in Table I.

In these decay chains, the α-decay signals of ^{224}Np and ^{220}Pa were piled up in the 15-μs recording cycle due to the short decay times of ^{220}Pa as shown in Table I. The pileup traces corresponding to the decay chains 1 and 2 are plotted in Fig. 1 as examples. Because of the short time difference between the implantation of ^{224}Np and its subsequent α decay in events 1 and 6, the ER-α_1-α_2 signals were all piled up in the same trace.

From events 1–3, the full α energies of both ^{224}Np and ^{220}Pa can be extracted. In event 4 (5), only partial α energy of ^{220}Pa (^{224}Np) was registered. In events 2 and 3, the α particle of ^{216}Ac escaped from the detector. The particle energy of ^{216}Ac in event 5 is different from others within the error bars, but it fits well with the literature value for decaying from the ground state of ^{216}Ac to the 4^+ first excited state in ^{212}Fr [9,11].

In events 1–4, the α particle energies of ^{224}Np are in agreement with each other within the error bars, while the α energies of ^{220}Pa in events 1–3 and 5 match well. Therefore, events 1–5 were attributed to one decay path starting from ^{224}Np through ^{220}Pa and to the ground state of ^{216}Ac (the α_1-α_2 path in Fig. 2). By taking a systematic uncertainty of 15 keV into account in the calculation of the energy error, an α energy of 9553(20) keV was extracted for ^{220}Pa from events 1–5, and the corresponding half-life was deduced to be 308^{+250}_{-95} ns. This α particle energy is very close to that of the ground-state decay (9520(16) keV) [6]. However, their half-lives are different within the error bars. Thus, the ground state of ^{224}Np may not directly decay to the ground state of

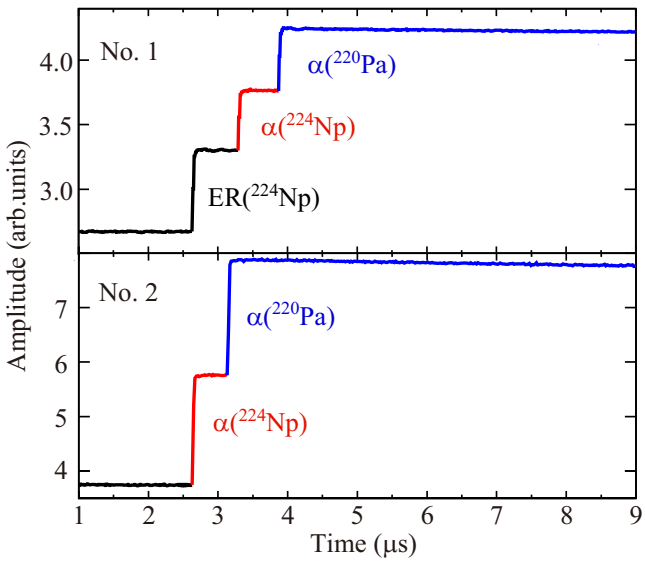

FIG. 1. Examples of the multiple pulse traces where α decays of ^{224}Np were registered.

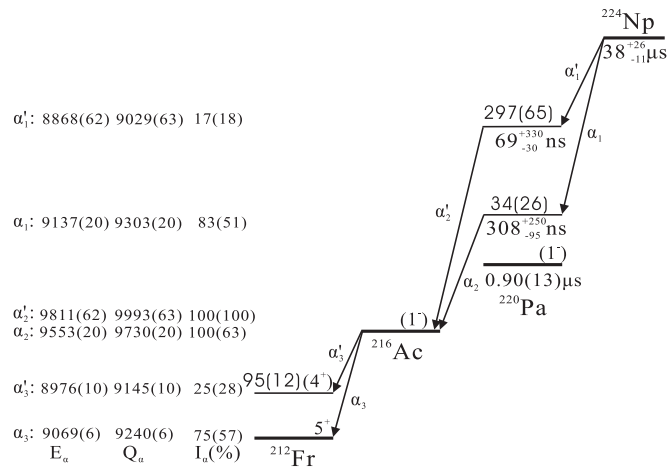

FIG. 2. Energy level scheme resulting from the present experiment. Both units are keV for the α particle energies, Q_α, and the excitation energies. A systematic uncertainty of 15 keV is taken into account in the calculation of the energy error. The Q_α values are extracted without screening correction [12]. The error bars of branching ratios represents statistical errors only.

^{220}Pa in this decay path, and the excitation energy of this level in ^{220}Pa was determined to be 34(26) keV. It is worth noting that in this paper the Q_α values are deduced following the approach in Ref. [12] without screening correction.

In event 6, the α energies of ^{224}Np and ^{220}Pa are different from that in events 1–5, but the third-generation α energy and decay time are consistent with the literature values for ^{216}Ac ground state [9–11], suggesting that another isomer of ^{220}Pa was populated in this decay chain. Its excitation energy and half-life were determined to be 297(65) keV and 69^{+330}_{-30} ns, respectively. The decay path corresponding to this event is labeled as α_1'-α_2' in Fig. 2.

The sum of the Q_α values for the two decay paths proposed above are 19033(28) and 19022(89) keV, respectively, identical within the error bars, implying that the two decay paths start from one same level in ^{224}Np. A half-life of $T_{1/2} = 38^{+26}_{-11}$ μs and α energies of 9137(20) and 8868(62) keV were determined for the two α branches in ^{224}Np. It is worth noting that although the α energies support decay from one level of ^{224}Np, the wide distribution of the decay times of ^{224}Np cannot exclude the possibility for decaying from more than one levels in ^{224}Np, whose excitation energies will be very close. The decay scheme proposed in the present work is shown in Fig. 2. The corresponding Q_α and relative intensities are listed to the left.

The production cross section for ^{224}Np was determined to be 380^{+260}_{-110} pb at 188 MeV with a SHANS transmission efficiency of 11(3)%, estimated by using the experimental cross sections for the ^{40}Ar + ^{175}Lu reaction [13]. The error bars represent statistical errors only and were calculated according to the method described in Ref. [14].

Neutron-deficient nuclei with N around 130 show transitional nature, with effects of the shell gap at $N = 126$ still evident, and quadrupole and octupole collectivity sets in [15]. This leads to quite uncommon shape competition effects and the level structures become more complex, especially for odd-odd nuclei. In the ground-state α decay of ^{220}Ac, an odd-odd $N = 131$ isotone, for example, more than 10 levels are populated in its daughter nucleus ^{216}Fr, and the relative intensity I_α for the ground-state to ground-state decay is ∼4% only [11,16], while for ^{222}Pa, its α-decay fine structure has not been identified very clearly yet and the experimental data is rare [11,17,18]. In the present experiment, the nonobservation of the ground-state to ground-state decay of ^{224}Np is consistent with the low branching ratios observed in these lighter odd-odd isotones.

IV. SUMMARY

The α-decay properties of the new isotope ^{224}Np have been studied via the fusion-evaporation reaction of ^{40}Ar + ^{187}Re using the digital pulse processing technique. Two α-decay branches of ^{224}Np were identified through spatial and temporal correlation measurements, populating two low-lying isomeric states in ^{220}Pa. Their energies and half-life were determined to be $E_{\alpha1} = 8868(62)$ keV, $E_{\alpha2} = 9137(20)$ keV, and $T_{1/2} = 38^{+26}_{-11}$ μs respectively.

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