α decay of the new neutron-deficient isotope ^{205}Ac

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The new neutron-deficient isotope ^{205}Ac was synthesized in the complete-fusion reaction ^{169}Tm(^{40}Ca, 4n)^{205}Ac. The evaporation residues were separated in-flight by the gas-filled recoil separator SHANS in Lanzhou and subsequently identified by the α-α position and time correlation method. The α-decay energy and half-life of ^{205}Ac were determined to be 7.935(30) MeV and 20^{+97}_{-9} ms, respectively. Previously reported decay properties of the ground state in ^{206}Ac were confirmed.

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I. INTRODUCTION

α-decay spectroscopy can provide structure information for the very neutron-deficient heavy nuclei close to the proton drip line. At present, the most efficient method of producing these short-lived nuclei is heavy-ion-induced fusion evaporation reactions. In this work, the new neutron-deficient isotope ^{205}Ac was synthesized in the fusion reaction ^{169}Tm(^{40}Ca, 4n)^{205}Ac.

II. EXPERIMENTAL DETAILS

The experiment was performed with a ^{40}Ca beam from the Sector-Focusing Cyclotron (SFC) of the Heavy Ion Research Facility in Lanzhou (HIRFL), China. The beam ions were accelerated to an energy of 198 MeV with a typical intensity of 100 pnA. A degrader titanium foil with a thickness of 2 μm was used to vary the bombarding energy. The target with a thickness of 400 μg/cm^2 was prepared by evaporating ^{169}Tm material on a carbon foil of 40 μg/cm^2 thickness and covered with a layer of 10 μg/cm^2 of carbon in order to improve the radiative cooling and reduce the material losses by sputtering. The effective beam energies at the center of target and irradiation times (in parentheses) were 196 MeV (61 h) and 183 MeV (19 h). These beam energies correspond to the maximum yields of the 4n and 3n evaporation channels, respectively, which are calculated by the code HIVAP [1]. The energy losses in the degrader foil and the target were calculated using the SRIM code [2].

The recoiled evaporation residues (ER) were separated in-flight from the primary beam particles using the gas-filled recoil separator SHANS (Spectrometer for Heavy Atoms and Nuclear Structure) [3]. The pressure of the helium filling gas in the separator was typically 0.8 mbar. After passing through two multiwire proportional counters (MWPC), the residues were implanted into a position sensitive silicon detector (PSSD). The recoil time-of-flight measurement using the gas counters allowed us to distinguish implantation events from radioactive decay events in the PSSD. The PSSD with a total active area of 150 × 50 mm^2 was divided into 48 vertical strips of 3 mm width. The vertical position (from −25 mm to 25 mm) was determined by the resistive charge deviation method, which gave a 1.5-mm vertical position resolution (FWHM) for each strip. Eight non-position-sensitive side silicon detectors (SSD), each with an active area of 50 × 50 mm^2, were mounted perpendicular to the face of the implantation detector. They were used to detect the escaping α particles. Behind the PSSD, three punch-though detectors were mounted in order to provide veto signals for energetic light particles passing through the strip detector. The thickness of all detectors was 300 μm. Silicon detectors were calibrated using external α sources and α-particle energies of ^{200}Po [5863(2) keV], ^{201}At [6344(2) keV], ^{204}Rn [6418.9(25) keV], ^{206}Fr [6790(4) keV], ^{205}Fr [6915(4) keV], and ^{204}Fr [7031(5) keV] isotopes which were produced during the irradiation and implanted into the detector. These α-particle energies were taken from Ref. [4]. The energy resolution with all strips summed was measured to be 70 keV (FWHM) at an α-particle energy of 6–7 MeV. The identification of the isotopes was based on the energy, time, and position correlations of implanted ERs and their subsequent α decays.

III. RESULTS AND DISCUSSION

Figure 1(a) presents the energy spectrum of all α particles measured in the PSSD in anticoincidence with the MWPC and punch-through detectors at the beam energy of 196 MeV. The

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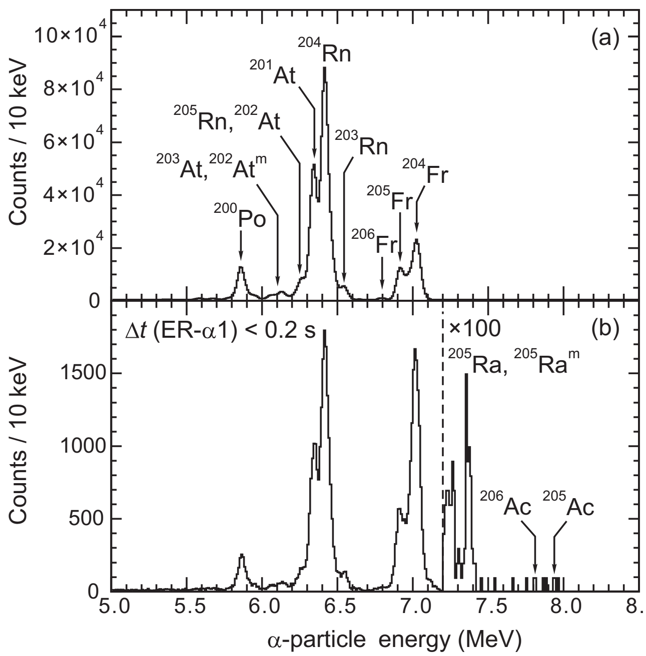

FIG. 1. Energy spectra of α particles measured in the silicon strip detector in anticoincidence with the MWPC and punch-though detectors in the reaction ^{40}Ca+^{169}Tm at 196 MeV: (a) all decays; (b) decays following recoil implants within 0.2 s. Notice the scale change at 7.2 MeV in (b). Only the prominent α peaks of known activities are marked.

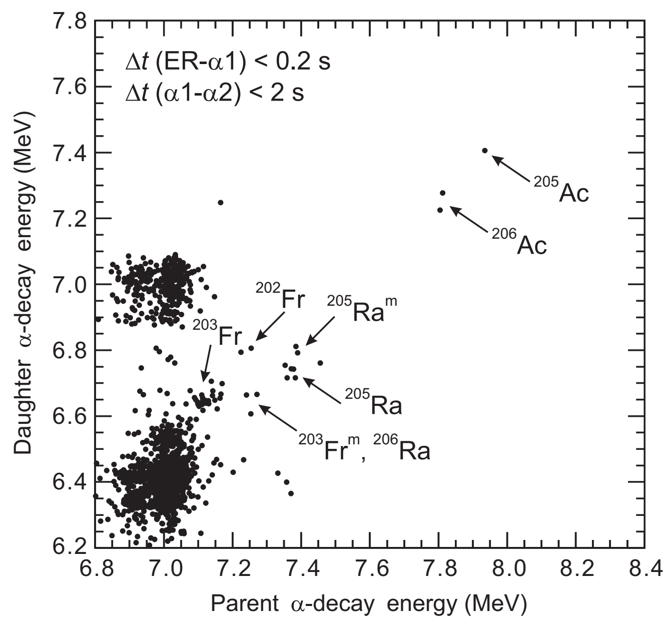

FIG. 2. Two-dimensional plot of parent and daughter α-decay energies for correlated ER-α_1-α_2 events observed in the reaction ^{40}Ca + ^{169}Tm at 196 MeV. Maximum search times for the ER-α_1 and α_1-α_2 pairs were 0.2 s and 2 s, respectively.

spectrum is dominated by the decays of Fr, Rn, and At isotopes and their subsequent descendants, which were formed in the charged particle evaporation channels. In Fig. 1(b), only α decays following recoil implants within a search time of 0.2 s are shown. The ^{205}Ra and ^{205}Ra^m isotopes produced in the $p3n$ channel are observed clearly. The arrows show the decay energies of ^{206}Ac and ^{205}Ac events observed in the correlated decay chains.

Using the time windows $\Delta t(\mathrm{ER}-\alpha 1) < 0.2$ s and $\Delta t(\alpha 1-\alpha 2) < 2$ s, a two-dimensional spectrum of parent-daughter (α1-α2) correlations measured in the PSSD is shown in Fig. 2. The radium and francium isotopes, ^{205,206}Ra, ^{205}Ra^m, ^{202,203}Fr, and ^{203}Fr^m, produced in the pxn and αxn channels, can be identified. The area where both the parent and daughter α-decay energies are around 7.0 MeV is strongly dominated by accidental correlations from the intense francium activities. In the region where the α-decay energies of parent activities are greater than 7.6 MeV, the α-decay correlations from actinium activities are clearly visible.

In previous studies, the most neutron-deficient actinium isotope observed was ^{206}Ac. Two α-decay isomeric states in ^{206}Ac were found by Eskola *et al.* [5]. One was assigned to a $J^\pi = (3^+)$ level and the other to a $J^\pi = (10^-)$ level. In Ref. [6], another isomeric state with higher decay energy in ^{206}Ac was reported. In the present experiment, three correlated α-decay events, including two quadruple correlation events and one triple event, were assigned to the decay of the known actinium isotope ^{206}Ac, which were produced from the $3n$ evaporation channel. They are listed in Table I (chains 1–3), together with the beam energies, implantation or decay energies, positions, time intervals between the subsequent decays, and also the strip numbers of the PSSD. Chains 1 and 2 were observed at the 196-MeV bombarding energy and chain 3 was observed at 183 MeV. In chain 2, no grand-daughter decay (α3) was observed due to the relatively high EC/β^+ branch of ^{198}At ($\sim$10% branching ratio [4]) or the escaping α-decay event whose deposited energy was lower than the discriminator level ($\sim$1 MeV) of the electronic circuit. The measured average α-decay energy and half-life of the parent nuclei are 7.817(30) MeV and 41^{+56}_{-15} ms, which are consistent with the decay of $J^\pi = (3^+)$ ground state in ^{206}Ac ($E_\alpha = 7.790(30)$ MeV, $T_{1/2} = 22^{+9}_{-5}$ ms) reported in Ref. [5]. For α2, the average α-decay energy and half-life are determined to be 7.245(30) MeV and $0.29^{+0.40}_{-0.11}$ s, respectively. These data are in good agreement with the reported decay properties of two isomeric states in ^{202}Fr, both of which have the same α energies ($E_\alpha = 7.237(8)$ MeV [7]) and half-lives ($T_{1/2} = 0.34(4)$ s [7]). According to the data from chains 1 and 3, the 6.724(30)-MeV average α-decay energy and $3.1^{+5.6}_{-1.2}$ s half-life of α3 are deduced, which are consistent with the decay of $J^\pi = (3^+)$ ground state in ^{198}At ($E_\alpha = 6.755(4)$ MeV, $T_{1/2} = 4.2(3)$ s [7]). Based on these facts, the parent α-decay activity of chains 1–3 can be unambiguously assigned to the decay of $J^\pi = (3^+)$ ground state in ^{206}Ac. The error of the half-lives was estimated by using the method of Ref. [8].

The fourth correlated decay chain listed in Table I was observed at the beam energy of 196 MeV. An implantation event with an energy of 12.2 MeV was followed 29.1 ms later by an α event with energy 7.935(30) MeV. Subsequently, the daughter and grand-daughter α decays were also observed at 7.406(30) MeV and 6.997(30) MeV.

TABLE I. Energies, positions and time intervals of correlated decay chains assigned to the isotopes ^{206}Ac and ^{205}Ac. Detector strips are numbered 0–47 from low to high magnetic rigidity.

Event no.	Beam energy (MeV)	Isotope	Type	Strip no.	Energy (MeV)	Position (mm)	Δt
1	196	^{206}Ac	ER	17	11.3	− 9.4	0
			$\alpha 1$	17	7.805	− 9.2	57.7 ms
			$\alpha 2$	17	7.225	− 9.8	18.6 ms
			$\alpha 3$	17	6.701	− 8.2	7.75 s
2	196	^{206}Ac	ER	30	11.8	− 9.4	0
			$\alpha 1$	30	7.812	− 7.9	14.7 ms
			$\alpha 2$	30	7.276	− 7.9	874 ms
3	183	^{206}Ac	ER	17	11.4	0.6	0
			$\alpha 1$	17	7.834	0.7	104.2 ms
			$\alpha 2$	17	7.235	0.8	372 ms
			$\alpha 3$	17	6.746	0.4	1.11 s
4	196	^{205}Ac	ER	22	12.2	− 0.9	0
			$\alpha 1$	22	7.935	− 1.0	29.1 ms
			$\alpha 2$	22	7.406	− 1.8	85.0 ms
			$\alpha 3$	22	6.997	− 1.6	2.08 s

The associated decay times of the two activities were 85.0 ms and 2.08 s, respectively. The whole decay chain was observed within a position window of 1 mm. The observed decay of $\alpha 2$ is consistent with the reported decay properties of the $(9/2^-)$ ground state of ^{201}Fr ($E_\alpha = 7.379(7)$ MeV, $T_{1/2} = 67(3)$ ms [9]) rather than with the decay of its $(1/2^+)$ isomeric state ^{201}Fr^m ($E_\alpha = 7.454(8)$ MeV, $T_{1/2} = 19^{+19}_{-6}$ ms [10]). For $\alpha 3$, although the observed time interval between $\alpha 2$ and $\alpha 3$ is about five times longer than the reported half-lives of 0.390(16) s [9] and 0.34(2) s [10] for the $(9/2^-)$ ground state of ^{197}At, the decay energy is consistent with the reported 6.963(4) MeV [9] and 6.959(6) MeV [10] of ^{197}At rather than with the decay of its $(1/2^+)$ isomeric state ^{197}At^m (6.707(5) MeV [11]). Therefore, we conclude that this correlated α-decay chain originates from the new isotope ^{205}Ac, which was produced in the $4n$ evaporation channel. The deduced decay energy and half-life of the new isotope are 7.935(30) MeV and 20^{+97}_{-9} ms, respectively. Due to the large probability for α decays occurring without changes of spin and parity, we conclude that the observed decay of ^{205}Ac originates most likely from its $(9/2^-)$ ground state. The measured decay properties of ^{206}Ac and ^{205}Ac along with the available literature data are summarized in Table II.

Based on the average counting rate of α-decay events within the 7.1–8.5 MeV energy window, the probability of accidental coincidences for ER-$\alpha 1$-$\alpha 2$ events during a time interval of 2 s is estimated to be 1.7×10^{-8}. The estimated probability that a decay chain is followed within 10 s by an unrelated α decay occurring in the 6.5–7.1 MeV energy window is 7.8×10^{-2}. Therefore, it is unlikely that any of the event chains in Table I is attributed to a random correlation of unrelated events.

Figures 3(a) and 3(b) present the systematics of the Q_α and $T_{1/2(\alpha)}$ values of isotopes $^{205-215}$Ac, respectively. It is shown

TABLE II. Measured α energies (E_α) and half-lives ($T_{1/2}$) of ^{206}Ac and ^{205}Ac and compared with available literature data.

Nuclei	E_α (MeV) (Present work)	$T_{1/2}$ (ms) (Present work)	E_α (MeV) (Literature)	$T_{1/2}$ (ms) (Literature)	J^π	Ref.
^{206}Ac	7.817(30)	41^{+56}_{-15}	7.790(30)	22^{+9}_{-5}	(3^+)	[5]
			7.750(20)	33^{+22}_{-9}	(10^-)	[5]
			7.894(50)	11^{+9}_{-3}		[6]
^{205}Ac	7.935(30)	20^{+97}_{-9}			$(9/2^-)$	

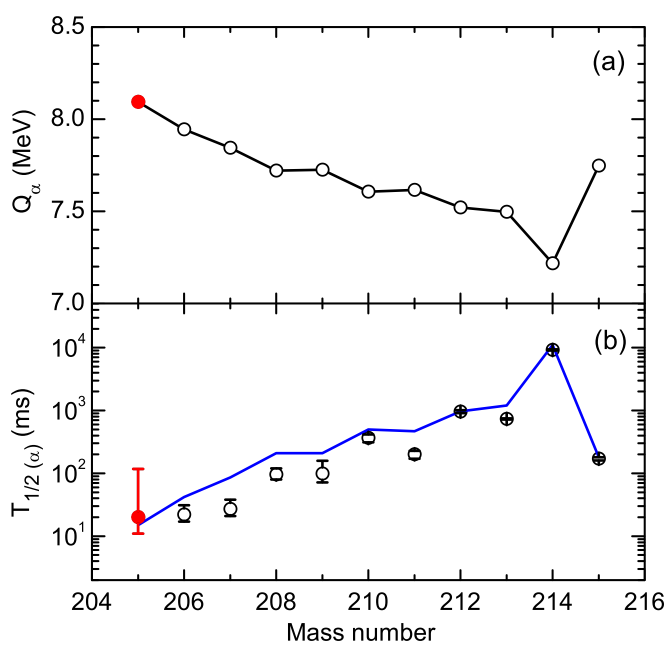

FIG. 3. (Color online) The systematics of Q_α-decay energies (a) and partial α-decay half-lives (b) for the favored $\Delta L = 0$ α-decay transitions of the $205 \leqslant A \leqslant 215$ actinium isotopes. The literature values (open circles) are taken from Refs. [4,5,12–14]. The values from our measurement for ^{205}Ac are marked by solid symbols. The solid line in (b) shows the calculated $T_{1/2(\alpha)}$ values according to Refs. [16,17].

that the measured values of ^{205}Ac in this work fit well into the systematics. According to the Rasmussen approach [15], the reduced α-decay width δ_α^2 of ^{205}Ac can be deduced to be 19^{+93}_{-9} keV for $\Delta L = 0$ transitions. It is comparable with the neighboring even-even nuclei ($\delta_\alpha^2(^{204}\mathrm{Ra}) = 73$ keV [10]) within experimental errors.

In Refs. [16,17], a new version of the Geiger-Nuttall law including the quantum numbers of α-core relative motion was proposed, which reproduces the α-decay half-lives of heavy nuclei with $N \leqslant 126$ very well. In Fig. 3(b), a calculation using this law is carried out for the favored α-decay transitions, and the results are compared with experimental values. The calculated 15-ms half-life of ^{205}Ac is in good agreement with the value measured in the present experiment.

The cross section of the production of ^{205}Ac was estimated to be about 70 pb at the 196-MeV bombarding energy. At 183 MeV, the cross section of ^{206}Ac was about 0.3 nb. In these measurements, a 14% transmission efficiency of the SHANS was assumed [3].

In conclusion, the new neutron-deficient isotope ^{205}Ac was identified in the complete fusion reaction of ^{40}Ca ions with the ^{169}Tm target. The α-decay energy and half-life of ^{205}Ac were determined. And the decay properties of the ground state in ^{206}Ac were confirmed.

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