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Letter

Alpha decay of the new isotope ^{215}U

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Abstract. The new neutron-deficient isotope ^{215}U was produced in the complete-fusion reaction ^{180}W(^{40}Ar, 5n)^{215}U. Evaporation residues recoiled from the target were separated in flight from the primary beam by the gas-filled recoil separator SHANS and subsequently identified on the basis of energy-position-time correlation measurement. The α-particle energy and half-life of ^{215}U were determined to be 8.428(30) MeV and $0.73^{+1.33}_{-0.29}$ ms, respectively.

1 Introduction

It has been reported that the α-decay energies of ground state to ground state transitions for neutron-deficient isotopes (Z = 84–91) located beyond the N = 126 follow the trend of increase with the decrease of neutron number [1–3]. In order to see if the α-decay properties of very neutron-deficient uranium isotopes follow this trend, we performed experiments with the aim to synthesize ^{216}U (N = 124) and ^{215}U (N = 123). If their decay properties follow this trend, the α-particle energies and half-lives of ground state to ground state transition for ^{215}U and ^{216}U will be similar to each other in analogy with the α-decay properties of other known 123-neutron isotopes and 124-neutron isotopes, such as ^{214}Pa and ^{215}Pa [4], ^{213}Th and ^{214}Th [5], ^{212}Ac and ^{213}Ac [4], ^{211}Ra and ^{212}Ra [6]. Recently we have observed the new isotope ^{216}U by the complete-fusion reaction ^{180}W(^{40}Ar, 4n)^{216}U [7]. The α-particle energies and half-lives were determined to be 8.384(30) MeV and $4.72^{+4.72}_{-1.57}$ ms for the ground state of ^{216}U and 10.582(30) MeV and $0.74^{+1.34}_{-0.29}$ ms for an isomeric state. In this paper, we will report the result of ^{215}U, synthesized by the ^{180}W(^{40}Ar, 5n)^{215}U reaction.

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2 Experiment

The experiment was performed at the gas-filled recoil separator SHANS [8] and the ^{40}Ar beam was delivered by the sector focusing cyclotron of the Heavy Ion Research Facility in Lanzhou (HIRFL), China. The typical beam intensities were about 150–250 pnA. The enriched ^{180}W targets (91.4% ^{180}W and 8.5% ^{182}W) with an average thickness of 481 μg/cm^2 were evaporated on carbon foils of 43 μg/cm^2 and covered with carbon layers of 14 μg/cm^2. The targets were mounted on a fixed frame. The experiment can be separated into two runs depended on the selected two beam energies. In the first run, a beam energy of 204.5 MeV was chosen on the basis of the expected maximum cross section for ^{215}U calculated by the HIVAP code [9]. When one correlated decay chain like the candidate of either ^{215}U or ^{216}U was observed after a irradiation time of 89 hours, we found it was difficult to determine which of the two isotopes should be assigned to because of their very close production cross sections and the very similar α-decay properties of the nuclei in the ^{215}U $\rightarrow$ ^{211}Th $\rightarrow$ ^{207}Ra and ^{216}U $\rightarrow$ ^{212}Th $\rightarrow$ ^{208}Ra chains [2,10,11]. In the second run, the beam energy was increased to 207.6 MeV. At this beam energy, the cross section of ^{215}U was estimated to be much higher than that of ^{216}U. Therefore, even though the decay proper-

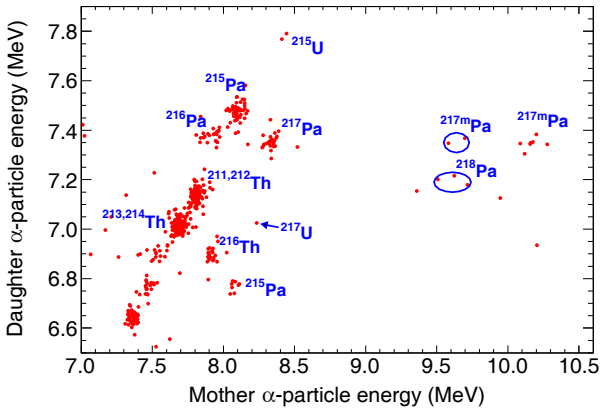

Fig. 1. (Color online) Mother and daughter α-particle energies for all chains of the type ER $\rightarrow \alpha_1 \rightarrow \alpha_2$ observed in the 205.5 MeV ^{40}Ar + ^{180}W irradiation. Maximum search times were 100 ms for the ER$\rightarrow\alpha_1$ pair and 5 s for the $\alpha_1\rightarrow\alpha_2$ pair.

ties of the two nuclei are much similar, we are able to distinguish them on the basis of their quite different cross sections. The estimated beam energies at the center of the target and the relevant irradiation times (in parentheses) in the two runs are 202.4 MeV (89 hours) and 205.5 MeV (157 hours), respectively. In the following, all beam energies mentioned in the text refer to the beam energies at the center of the target.

After filtering out by the separator, the evaporation residues (ERs) were implanted into three 300 μm thick position-sensitive strip detectors (PSSDs) installed side by side at the focal plane of the separator. Each PSSD, with an active area of 50 × 50 mm^2, was divided into 16 vertical strips in the front face. The energy resolution with all strips summed was about 70 keV (FWHM) for 5–9 MeV α particles and the vertical position resolution was about 2.5 mm (FWHM). Upstream the PSSDs, eight non–position-sensitive silicon detectors (side detectors) of similar type were mounted. The PSSDs and the side detectors formed a Si-box detector. The efficiency of the Si-box detector for detecting an α particle with full energy was about 80% of 4π. In order to distinguish the α-decay events from the implantation events, two multi-wire proportional counters (MWPCs) were mounted 15 cm and 25 cm upstream from the PSSDs. α-particle energy calibrations were performed using a three-peak external α source as well as the peaks from nuclides produced in the test reaction ^{40}Ar + ^{175}Lu.

3 Results

The identification of the products was performed using the method of energy-position-time correlated α-decay chains. A two-dimensional plot showing the correlation between parent and daughter α-particle energies of type ER $\rightarrow$ $\alpha_1 \rightarrow \alpha_2$ is shown in fig. 1. The analysis of the correlation was made with a vertical position window of ±2.5 mm and the time windows of 100 ms for ER $\rightarrow \alpha_1$ pair and 5 s for $\alpha_1 \rightarrow \alpha_2$ pair. In this plot different isotopes $^{211-214}$Th, ^{216}Th, $^{215-218}$Pa and ^{217}U can be identified. However, the presence of ^{216}Th, ^{216,217}Pa and ^{217}U was explained by the admixture of ^{182}W isotope in the ^{180}W target. In addition a group of two correlated chains assigned to ^{215}U was also observed. These events are listed in table 1, together with the beam energies, vertical positions, measured energies, and also the time intervals between the subsequent decays.

Table 1. Beam energies ($E_{\rm lab}$), vertical positions, measured energies and time intervals (ΔT) of correlated chains assigned to the decays of ^{215}U.

$E_{\rm lab}$ (MeV)	Nuclei	Type	Position (mm)	Energy (MeV)	ΔT
205.5	^{215}U	ER	−15.7	13.59	0
		α_1	−14.9	8.414	0.776 ms
		α_2	−15.9	7.767	59.7 ms
		α_3	−13.6	7.289[(a)]	0.73 s
205.5	^{215}U	ER	11.9	12.61	0
		α_1	11.4	8.442	1.33 ms
		α_2	13.4	7.792	0.43 ms
		α_3	11.7	7.127	0.23 s

[(a)] Escaped α-particle energy reconstructed by summing up the two energies deposited in the PSSD and side detector.

The two correlated chains were observed at the beam energy of 205.5 MeV. Based on the two decay chains, the α-particle energy and half-life of the daughter nucleus were determined to be 7.780(30) MeV and $20.8^{+37.9}_{-8.2}$ ms, which are consistent with the α decays from ^{211}Th (E_α = 7.792(14) MeV, $T_{1/2} = 37^{+28}_{-11}$ ms) [2] and ^{212}Th (E_α = 7.809(5) MeV, $T_{1/2}$ = 31.7(13) ms) [10]. The observed granddaughter decays are consistent with the α decays from ^{207}Ra and ^{208}Ra, whose α-particle energies and half-lives are 7.131(5) MeV and 1.3(2) s for ^{207}Ra [11] and 7.131(5) MeV and 1.2(2) s for ^{208}Ra [11], respectively. The α_3 in the first decay chain escaped from the PSSD and its energy was recovered by summing up the energies deposited in the PSSD (2.740 MeV) and the side detector (4.549 MeV). The recovered value 7.289 MeV is also in agreement with the literature value 7.131(5) MeV within the error limit of 200 keV. The probability of random correlation [12], calculated on the basis of observed average counting rates in the detectors, was estimated to be less than 2.04×10^{-11} and the expected number of random correlation was about 1.4×10^{-4}. So these two decay chains were considered to be real correlation. Due to the similarities in the α decays of ^{215}U and ^{216}U, it is not possible for us to make an unambiguous identification of the two observed decay chains based on decay properties alone. However we prefer to assign these two decay chains to ^{215}U on the basis of other two important facts.

Firstly, we can be sure that these two isotopes have a mass number less than 216 because they are formed at higher excitation energy in the ^{40}Ar + ^{180}W system than that required to produce the ^{216}U. In the experiment to study ^{216}U [7], a beam of ^{40}Ar at an energy of 187.2 MeV was used. At this beam energy (E^* = 45.7 MeV) 4 nucleons evaporation channels are dominant, which can be confirmed by the observation of ^{216}U (4n channel), ^{216}Pa (p3n

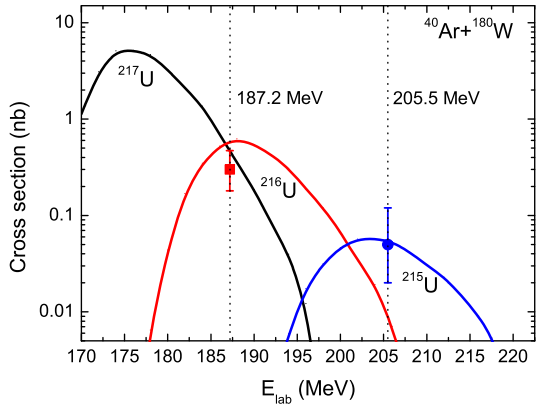

Fig. 2. (Color online) Excitation functions of the 3–5n evaporation channels of the reaction ^{40}Ar + ^{180}W calculated with HIVAP code [9] using its standard parameter set except that the fission barrier scaling factor $C_f = 0.63$ was used. The red square denotes the cross section of ^{216}U measured in ref. [7] and the blue circle denotes the cross section of ^{215}U measured in the present work. The error bars only represent statistical errors.

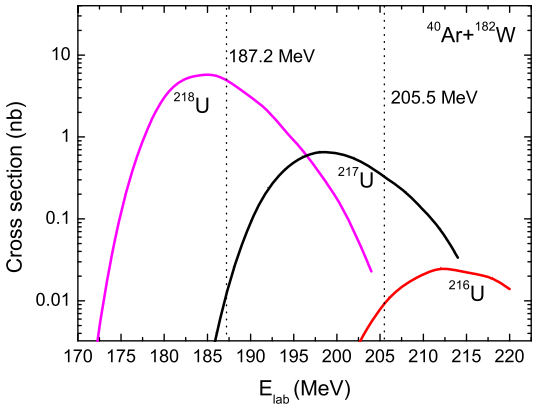

Fig. 3. (Color online) Excitation functions of the 4–6n evaporation channels of the reactions ^{40}Ar + ^{182}W calculated with HIVAP code [9] using its standard parameter set except that the fission barrier scaling factor $C_f = 0.63$ was used.

channel) and ^{218}U produced in the ^{182}W(^{40}Ar, 4n)^{218}U reaction. However, at the beam energy of 205.5 MeV in this experiment, the excitation energy of the compound nucleus is about 60.3 MeV, which is 14.6 MeV higher than that required to produce ^{216}U. With this beam energy, 5 nucleons evaporation channels should be dominant in this experiment. This can be confirmed by the observation of ^{215}Pa (p4n channel) and ^{217}U produced in the ^{182}W(^{40}Ar, 5n)^{217}U reaction. All above discussions are accord with excitation functions calculated with HIVAP code [9] (shown in fig. 2). The calculations were carried out using its standard parameter set except that the fission barrier scaling factor C_f was adjusted into 0.63 according to the analysis in [13]. As shown in fig. 2, the cross section of 5n channel is much higher than that of 4n channel at the beam energy of 205.5 MeV.

Secondly, the two decay chains are unlikely to be ^{216}U produced in 6n evaporation channel from ^{182}W component in the target, although some products such as ^{216,217}Pa and ^{217}U observed in this experiment could be more likely produced from ^{182}W component. Because at the beam energy of 205.5 MeV the cross sections of ^{216}U produced in the ^{182}W(^{40}Ar, 6n)^{216}U reaction was estimated to be about 9 pb, which is much smaller than that of ^{216}Pa (15 nb), ^{217}Pa (19 nb) and ^{217}U (0.35 nb). This can be partly seen in fig. 3. According to the proportions of these cross sections, it is unlikely to observe two ^{216}U when there are not many ^{216}Pa (25 chains), ^{217}Pa (40 chains) and ^{217}U (1 chain) to be produced.

Based on the two facts mentioned above, we concluded that the observed two correlated decay chains correspond to the α decays of the new isotope ^{215}U. The obtained α-particle energy and half-life for ^{215}U are 8.428(30) MeV and $0.73^{+1.33}_{-0.29}$ ms, respectively. In the present work the determination of the half-lives was made by the method reported in [14]. Using a transmission efficiency of 14% [8],

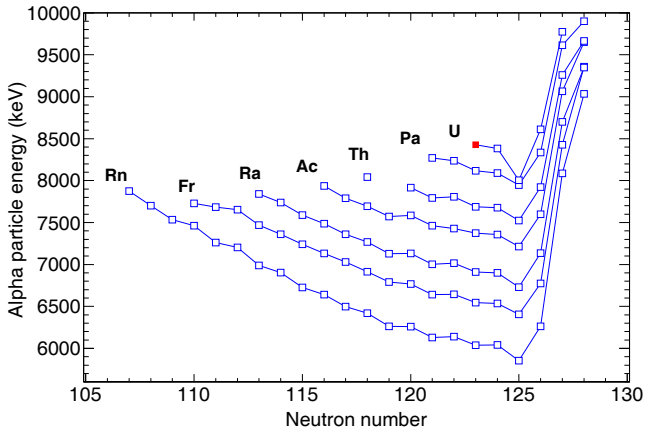

Fig. 4. (Color online) α-particle energies of ground state to ground state transitions for neutron-deficient Rn, Fr, Ra, Ac, Th, Pa and U isotopes (except ^{209}Th). Open squares refer to literature values taken from refs. [2,4–7,10,11,15–18]. The red soild square refers to the value of ^{215}U measured in this work. Although one α-particle energy of 8.005(20) MeV for the α decay of ^{217}U has been reported in [15] and this value has been plotted in this figure, it may not be the α-particle energy of the ground state to ground state transition for ^{217}U, due to its significant deviation from the systematic regularities. However, this assumption needs to be confirmed by further experiments.

the cross section for ^{215}U at the beam energy of 205.5 MeV was determined to be 50^{+70}_{-30} pb. The production cross section for ^{216}U has been measured to be 300^{+170}_{-120} pb at the beam energy of 187.2 MeV. The error bars of the measured cross sections only represent statistical errors determined by the method described in [14]. These measured values are consistent with the HIVAP calculation very well (see fig. 2).

The measured α-particle energy of ^{215}U fits well into the systematics of neutron-deficient U isotopes (shown in fig. 4) and it is also consistent with the systematic reg-

ularities observed in the α decay of neutron-deficient Rn isotopes through Pa isotopes. The reduced width δ^2 for the α decay of ^{215}U was calculated to be 173^{+316}_{-70} keV using the Rasmussen approach for $\Delta L = 0$ transitions [19]. These values, when compared to the values obtained for the closest even-even neighbors for the ground state to ground state decays (20–70 keV), show that this decay is an unhindered α decay. In order to reproduce the half-live, empirical formulae ($\Delta L = 0$) given in ref. [20] relating half-life and Q_α were used. And the calculated half-life for ^{215}U is 2.36 ms, which is very close to our measured value $0.73^{+1.33}_{-0.29}$ ms.

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