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Alpha Decay of the Neutron-deficient Isotopes ^{215,216}U

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Abstract: The most neutron-deficient isotopes ^{215,216}U were produced in the complete-fusion reaction ^{180}W(^{40}Ar, 4-5n)^{215,216}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 correlated α-decay chains. Two α-decaying states were identified in ^{216}U, one for the ground state and the other for the isomeric state with $8^+(\pi h_{9/2}\pi f_{7/2})$ configuration. The α-decay properties for ^{215,216}U and the systematics of 8^+ isomeric state in $N=124, 126$ isotones were investigated.

Key words: complete-fusion reaction; uranium isotope; α-decay energy; half-life

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1 Introduction

α-decay spectroscopy is a powerful tool to obtain the mass and structure information on the heavy nuclei close to the proton drip line. At and near $N=126$ spherical shell closure, there are only a few researches performed on the most neutron-deficient uranium isotopes[1–3]. In our previous experiments, the new uranium isotopes ^{215,216}U have been identified based on the correlated α-decay chains[4–5]. Additionally, in this region of the chart of nuclei, the isomeric states are of special interest, since they provide relatively pure and detailed information on the single-particle structure of these nuclei. In the $N=124$ and $N=126$ isotones, an isomeric state with $8^+(\pi h_{9/2}\pi f_{7/2})$ configuration has been significantly observed up to ^{214}Th[6] and ^{218}U[3], which behaves as an intruder state based on the attractive interaction of $f_{7/2}$ protons and $f_{5/2}$ neutrons in the framework of the seniority model.

The goal of the present work was to investigate the α-decay properties of the most neutron-deficient uranium isotopes ^{215,216}U and extends the systematics of isomeric states in $N=124$ isotones by searching for an $I^\pi=8^+$ isomer in ^{216}U.

2 Experimental details

The nuclei to be studied were produced in the complete-fusion reaction ^{180}W(^{40}Ar, 4-5n)^{215,216}U. The ^{40}Ar beam was delivered by the Sector Focusing Cyclotron (SFC) of the Heavy Ion Research Facility in Lanzhou (HIRFL), China. The incident beam energies of 189.5 MeV, 204.5 MeV and 207.6 MeV were chosen, which correspond to compound-nuclei excitation energies of 45.7 MeV, 57.9 MeV and 60.4 MeV, respectively, calculated for reaction at half-thickness of the target. The enriched ^{180}W target (91.4% ^{180}W and 8.5% ^{182}W) with an average thickness of 481 μg/cm^2 was evaporated on carbon foil of 43 μg/cm^2 and covered with carbon layer of 14 μg/cm^2.

Evaporation residues (ERs) were separated from the projectile-like and target-like particles by the gas-filled recoil separator SHANS (Spectrometer for Heavy

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Atoms and Nuclear Structure). After filtering out by the separator, the ERs were implanted into three 300 μm thick position sensitive strip detectors (PSSD), which were installed side by side at the focal plane of the separator. The PSSD with a total active area of 150 mm×50 mm was divided into 48 vertical strips of 3 mm width. 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). Eight non-position sensitive side silicon detectors (SSD), each with an active area of 50 mm ×50 mm, were mounted perpendicular to the face of PSSD. They were used to detect the escaping α particles. Behind the PSSD, three punch-though detectors were mounted to provide veto signals for energetic light particles passing through the strip detector. In order to distinguish the α-decay events from the implantation events, one or two multi-wire proportional counters (MWPC) were mounted upstream from the PSSD. 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. Details of the detection system and analysis procedure were described in our previous papers[4–5,7].

3 Results and discussions

3.1 ^{216}U

The identification of the aimed nuclides was based on the method of position-time correlation measurement. During the irradiation at 189.5 MeV beam energy, two α activities were assigned to the decay of ^{216}U. The first activity represents the 0^+ ground state to 0^+ ground state α-particle decay. Four decay chains originating from ^{216}U with $E_\alpha = 8.384(30)$ MeV and $T_{1/2} = 4.72^{+4.72}_{-1.57}$ ms were observed, in which all of the parent α particles were registered by the PSSD with full energy . For the other activity, the isomeric state of ^{216}U with $E_\alpha = 10.582(30)$ MeV and $T_{1/2} = 0.74^{+1.34}_{-0.29}$ ms was identified based on two correlated decay chains. In one of the chains the energy of the parent α particle was deduced from the sum of the PSSD and SSD energy deposition due to the occurrence of escaping event. In addition, one decay chain in which the parent α particle energy was about 200 keV lower than the above mentioned 8.384 MeV was observed. As the decay of corresponding daughter and granddaughter descendants can be associated with the known isotopes ^{212}Th and ^{208}Ra clearly, we also assign it to the decay

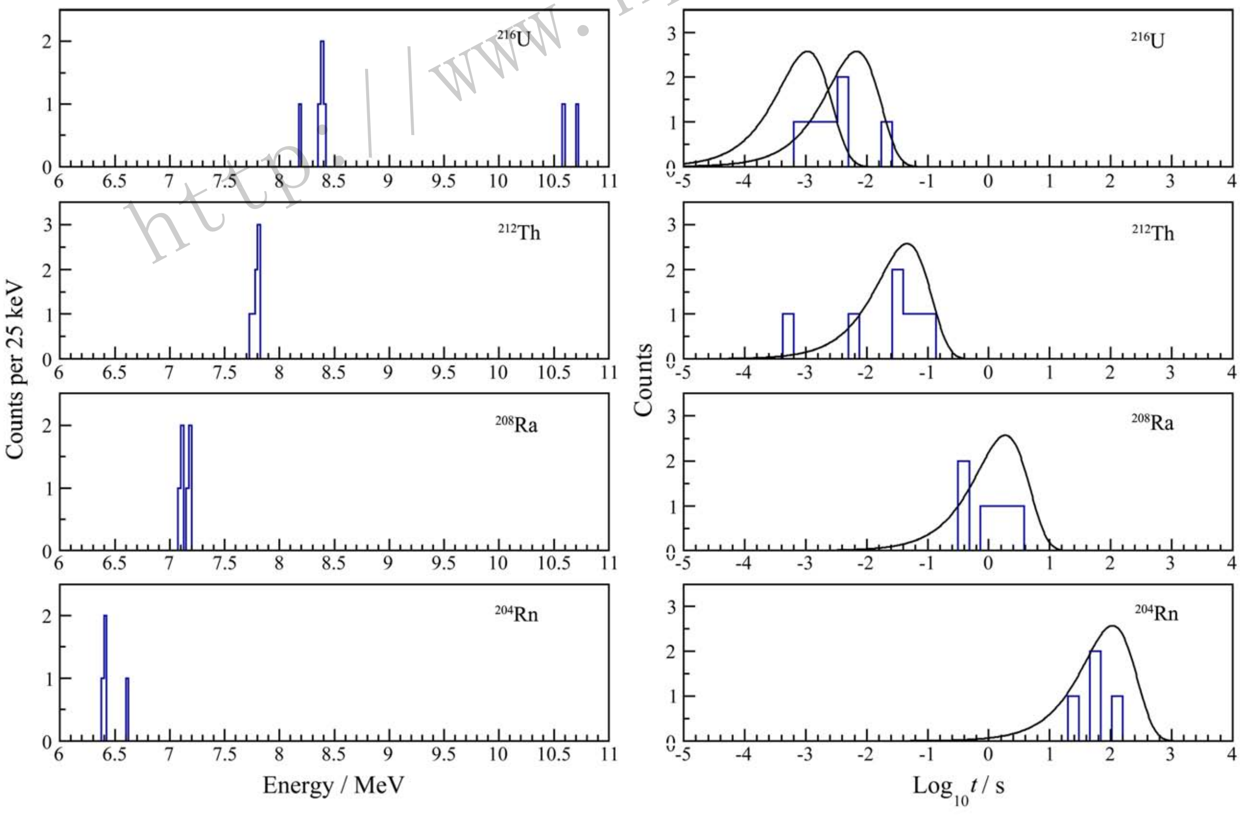

Fig. 1 (color online) Left panel: Measured energy spectra of the correlated α-decay events beginning from ^{216}U and ^{216m}U. Right panel: Decay time distributions of ^{216}U and ^{216m}U and their subsequent decays observed in the ^{40}Ar+^{180}W reaction. Logarithm of the decay time is taken as the abscissa. The solid curve indicates the calculated time distributions, for which the mean lifetimes are taken from the present work and literature values[8].

of ^{216}U. The detailed data are reported in our previous paper[5]. Fig. 1 shows the summarized energy and decay time distributions for the measured chains of ^{216}U.

To obtain information on the structure of the decaying state, we performed the reduced α-decay width δ^2 calculations according to the Rasmussen method[10]. The comparison of the α-decay schemes and partial α-decay half-lives for the neighbouring even-even nuclei ^{216,218}U and ^{214,216}Th is presented in Fig. 2. The reduced width values of ^{216}Th shown in Fig. 2 are calculated taking into account the α-decay branch values given in Ref. [9]. For other isotopes, a 100% α-decay branch value is assumed.

For the α activity between 0^+ ground states, it can be seen that the reduced width value of ^{216}U (34 keV) is comparable with the corresponding values of ^{218}U (66 keV), ^{214}Th (54 keV) and ^{216}Th (26 keV). This indicates the decay with the energy of 8.384 MeV is unhindered. In addition, if assuming this ground-state decay with zero angular-momentum change, the calculated half-life of ^{216}U according to the semi-empirical formula of Ref. [11] is in good agreement with the value measured in the present experiment.

The other α activity with 10.582 MeV energy in ^{216}U was assigned to the decay from the 8^+ isomeric state in ^{216}U to the 0^+ ground state in ^{212}Th as shown in Fig. 2. The comparison of the reduced width values of ^{216m,218m}U and ^{216m}Th indicates that the structures of these 8^+ isomeric states have the same origin.

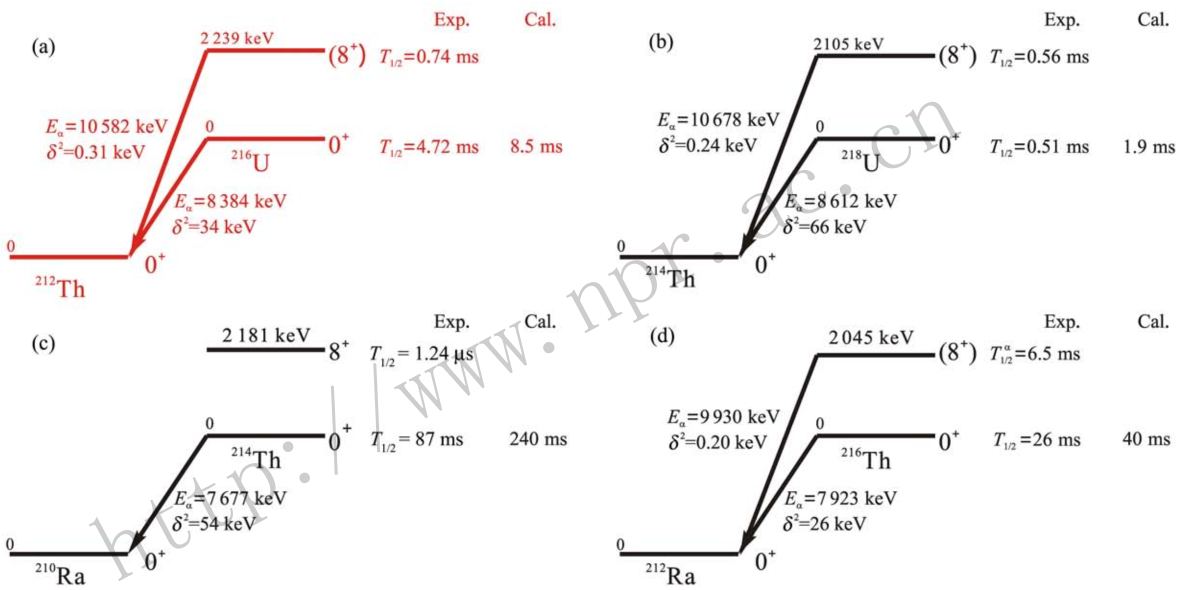

Fig. 2 (color online) α-decay schemes and partial α-decay half-lives of the even-even nuclei ^{216}U (a), ^{218}U (b), ^{214}Th (c) and ^{216}Th (d). The data for ^{216}U including the level energy, α-decay energy and half-life are from the present work, while other data are taken from Refs. [3, 6, 9]. ^{216m}U refers to the proposed 8^+ isomeric level. The reduced α-decay width δ^2 were calculated with the Rasmussen prescription [10]. The theoretical ground-state half-lives are calculated according to Ref. [11].

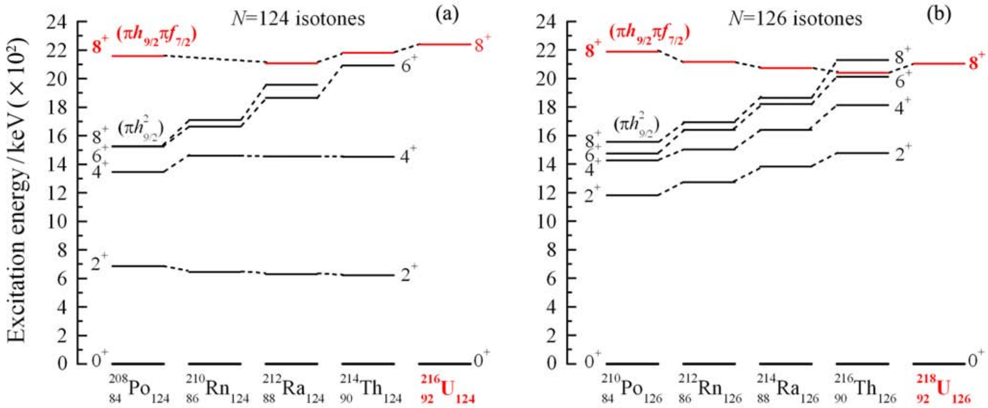

Fig. 3 (color online) Experimentally known low-lying levels in $N = 124$ (a) and $N = 126$ (b) even-Z isotones. The data are taken from Refs. [3, 6, 8-9] and the present work. The dash lines connect levels of equal spin and parity.

Fig. 3 shows the experimentally known low-lying levels in even-even $N = 124$ and $N = 126$ isotones above lead. It can be seen that the second 8^+ state with a dominating $(\pi h_{9/2}\pi f_{7/2})$ configuration exhibits the intruder behavior. In ^{214,216}Th and ^{218}U isotopes, this intruder state is located even below the $8^+(\pi h^2_{9/2})$ and $6^+(\pi h^2_{9/2})$ states, respectively, due to the increased attractive interaction of $f_{7/2}$ protons and $f_{5/2}$ neutrons[3, 6, 9]. Analogously, it is predicted that in the case of ^{216}U the $8^+(\pi h_{9/2}\pi f_{7/2})$ state falls below the $6^+(\pi h^2_{9/2})$ state forming an yrast trap. Based on the α-decay energies observed in the present work, the excitation energy of the $8^+(\pi h_{9/2}\pi f_{7/2})$ state in ^{216}U is determined as 2 239 keV. This is in good agreement with the value of ^{214,216}Th and ^{218}U isotopes (Fig. 2).

3.2 ^{215}U

The production of ^{215}U was studied at the beam energies of 204.5 MeV and 207.6 MeV, which corresponds to the maximum cross section for the 5 n evaporation channel according to the prediction by HIVAP code[12]. Two decay chains were identified in which the parent activity with $E_{\alpha1} = 8.428(30)$ MeV, $T_{1/2} = 0.73^{+1.33}_{-0.29}$ ms was followed by a daughter activity with $E_{\alpha2} = 7.780(30)$ MeV, $T_{1/2} = 20.8^{+37.9}_{-8.2}$ ms and by a granddaughter activity with $E_{\alpha3} = 7.127(30)$ MeV, $T_{1/2} = 0.33^{+0.61}_{-0.13}$ s. On the basis of the known α-decay data and calculated excitation function, the daughter decay can be attributed to ^{211}Th ($E_\alpha = 7.792(14)$ MeV, $T_{1/2} = 37^{+28}_{-11}$ ms)[13] and the granddaughter decay can be attributed with ^{207}Ra ($E_\alpha = 7.131(5)$ MeV, $T_{1/2} = 1.3(2)$ s)[14], so the parent α decay can be assigned to ^{215}U unambiguously. The experimental details and data analysis were reported in Ref. [4].

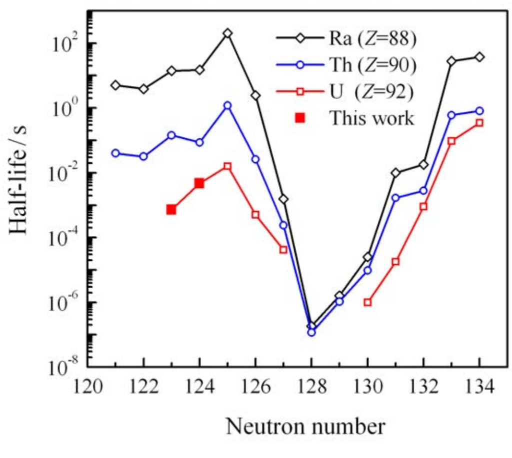

Fig. 4 (color online) Systematics of partial α-decay half-lives of the Ra, Th and U isotopes. The data of ^{215,216}U from this work are shown in solid squares. Other data are taken from Ref. [8].

To investigate the α-decay systematics in this region of nuclei, a comparison of partial α-decay half-lives of U isotopes with the values of even-Z Th and Ra isotopes is presented in Fig. 4. The analogous trend in the behaviour of the half-lives of U, Th and Ra isotopes can be seen. However, for the most neutron-deficient uranium isotopes, it can be seen that the experimental half-life values decrease almost exponentially with the decrease of neutron number from $N = 125$ to 123. This is slightly different with the trend of the behaviour of Th and Ra isotopes.

4 Conclusions

The most neutron-deficient isotopes ^{215,216}U have been identified unambiguously by observing the correlated α-decay chains leading to their know daughter products. Two α-decaying states were observed in ^{216}U, one for the ground state and the other for the isomeric state. In analogy to isomeric states in ^{218}U and ^{214,216}Th, the α-decaying isomer in ^{216}U is suggested to have the configuration $8^+(\pi h_{9/2}\pi f_{7/2})$, which exhibits the intruder behaviour. The systematics of the α-decay half-lives for the most neutron-deficient uranium isotopes is slightly different with the trend of the behaviour of the neighbouring even-Z Th and Ra isotopes.

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