α-decay properties of ^{220}Pa

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The isotope ^{220}Pa produced in the reaction ^{40}Ar + ^{187}Re at a beam energy of 198.7 MeV was reinvestigated via the α-spectroscopic method. A new α-decaying state in ^{220}Pa has been observed with an energy $E_\alpha = 9664(40)$ keV and with a half-life $T_{1/2} = 233^{+108}_{-56}$ ns. The spin parity of the state is tentatively suggested to be (3^-). The α energy and half-life of the (1^-) ground state are measured to be $E_\alpha = 9548(30)$ keV and $T_{1/2} = 0.75(8)$ μs, respectively. The reduced α width, inferred from the present data, fits well into the systematics for $N = 129$ isotones.

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I. INTRODUCTION

In the *trans-lead* neutron-deficient region, the nuclides decay pervasively by emitting α particles. α decays are then a valuable source of information on α energies, transition rates, and fine-structure patterns contributing to our knowledge of nuclear structure. The nucleus ^{220}Pa, located in this region, has been previously studied using α spectroscopy in several separate runs. In 1987, the decay properties of ^{220}Pa was reported by Faestermann *et al.* [1], who produced it using the ^{19}F + ^{204}Pb reaction. The α-line $E_\alpha = 9.65(5)$ MeV with a corresponding half-life $T_{1/2} = 0.78(16)$ μs was observed. In the same year, one α ray with $E_\alpha = 9.160(55)$ MeV and $T_{1/2} = 1.1(0.1)$ μs was reported by Miyatake *et al.* [2]. Later, Huang *et al.* [3] reproduced it by the reaction ^{40}Ar + ^{187}Re at a beam energy of 188 MeV. A half-life 0.90(13) μs was deduced for ^{220}Pa, and its α energy was determined to be 9520(16) keV. It can be seen that the decay properties of ^{220}Pa presented in the papers are slightly inconsistent with each other. Moreover, recent investigations of the α decay of the chain ^{224}Np $\rightarrow$ ^{220}Pa $\rightarrow$ ^{216}Ac yielded information on the excited low-lying levels of ^{220}Pa [4]. A J^π assignment was not performed yet due to the complexity of the spectroscopy. In the present paper, the ^{220}Pa nucleus has been produced and a new α-decay chain has been studied using both position and time correlations between the α decays of ^{220}Pa and ^{216}Ac. The purpose of the present paper is to see if we can throw additional experimental light on the low-lying states in ^{220}Pa and remove the disagreement on the assignment of the ground-state (g.s.) α line.

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II. EXPERIMENT

The experiment was carried out using the Sector-Focusing Cyclotron of the Heavy Ion Research Facility in Lanzhou (HIRFL), China. The primary aim of the experiment was to study the α-decay properties of new isotope ^{222}Np, and, thus, the experimental conditions were optimized for that purpose. Details of the experiment and the results concerning ^{222}Np have been reported elsewhere [5]. A beam of ^{40}Ar ions with energy of 198.7 MeV was incident upon a 250-μg/cm^2 ^{187}Re target, which was prepared by sputtering the material on to an 80-μg/cm^2-thick carbon foil. Reaction products [evaporation recoils (ERs)] were separated from the primary beam by the gas-filled recoil separator Spectrometer for Heavy Atoms and Nuclear Structure (SHANS). On the exit of the SHANS, the reaction products passed through a multiwire proportional counter before being implanted into one of three adjacent position-sensitive 16-strip detectors (PSSDs). Behind the PSSDs, three punch-through silicon detectors were positioned for the rejection of signals produced by energetic light particles. Signals from all the preamplifiers of detection system were recorded by a digital data-acquisition system, which consists of 16 wave-form digitizers V1724 from CAEN S.P.A. [6].

The PSSDs were initially calibrated using a mixed α source of ^{239}Pu, ^{241}Am, and ^{244}Cm, which emit α particles with energies in the range of 5 to 6 MeV. Additionally, an internal calibration of PSSD strips was performed using the dominant α-decay peaks from the nuclei produced in the irradiations with ^{175}Lu and ^{186}W targets.

III. RESULTS AND DISCUSSION

In the search for ^{220}Pa, it was required that an implant occurred, followed by two successive decays ($\alpha 1$, $\alpha 2$) in the

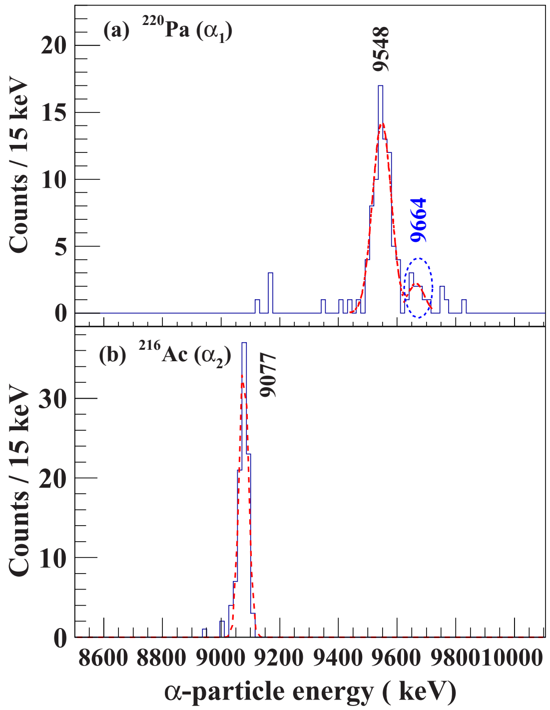

FIG. 1. Energy spectra from the PSSDs. Panels (a) and (b) show the energies of the first ($\alpha1$) and second ($\alpha2$) decays when it is required that the decays occur following an implant in the same place (a vertical position window of ±1.5 mm) and that $\alpha1$ occurs within 4.5 μs of ER, preceding the $\alpha2$ lines with the energy range of 8940–9160 keV, and $\alpha2$ occurs within 2 ms of $\alpha1$, respectively. The values written vertically on the panels give the energies associated with the centroids. The newly observed events from ^{220}Pa are labeled by the blue dotted ellipse.

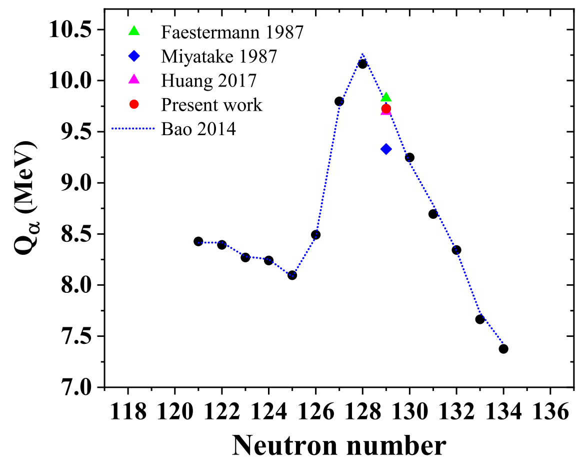

FIG. 2. α-decay energies Q_α of g.s.-to-g.s. transitions for the neutron-deficient Pa isotopes. The black solid circles represent literature values taken from Ref. [12]. The red solid circle refers to the value of ^{220}Pa measured in the present paper, compared to the values deduced from Faestermann *et al.* [1], Miyatake *et al.* [2], and Huang *et al.* [3]. The dashed line refers to the theoretical predictions taken from Bao *et al.* [8].

same place (a vertical position window of ±1.5 mm) of the PSSDs and that all signals (implant plus two decays) were received within a 2-ms period. It was initially required that $\alpha1$ was emitted within 4.5 μs [$\approx 5T_{1/2}(^{220}\text{Pa})$] [3] of ER, and $\alpha2$ decay within 2 ms [$\approx 5T_{1/2}(^{216}\text{Ac})$] [7] of $\alpha1$. In addition, we searched for events preceding the α lines of 9070 and 8992 keV of ^{216}Ac^g and 9106 and 9028 keV of ^{216}Ac^m [7], choosing energy range of 8940–9160 keV. With that kind of demand, a total of 95 events were selected. For these events, the energies of the first ($\alpha1$) and second ($\alpha2$) α decays recorded by the PSSDs are shown in Figs. 1(a), and 1(b), respectively.

In the spectrum for $\alpha1$, 72 α-decay events with energy $E_\alpha = 9548$ keV were attributed to the g.s.-to-g.s. transition of ^{220}Pa into ^{216}Ac. That energy is in agreement with the value given in Ref. [3] within error bars but not with the values in Refs. [1,2]. The deduced Q_α from the present paper fits well into the systematics of α-decay energies of g.s.-to-g.s. transitions for the neutron-deficient Pa isotopes, and a nice agreement with the predicted values [8] (see Fig. 2). Besides, the spectrum has a cluster of counts with a relatively wide distribution within the energy range of 9600–9720 keV. The centroid of these counts is at 9664 keV, which is an unknown α line. The α lines at the corresponding energy for the low-lying states reported in Ref. [4] cannot be verified in the present experiment since they are likely hidden under much stronger α groups from the ground state of ^{220}Pa. In the case of $\alpha2$, assigned to be the decay of ^{216}Ac, a well-pronounced single peak at energy 9077 keV was detected, in agreement with the literature value for the (1^-) ground state [7].

The time intervals between successive events in the chain ER-$\alpha1$-$\alpha2$ can be used to figure out the half-lives of each of the decays. Figures 3(a)–3(c) show the time distributions between (ER and $\alpha1$) and ($\alpha1$ and $\alpha2$), respectively. By applying the prescription proposed by Schmidt [9] and Schmidt *et al.* [10] to these data, the values of the half-lives have been allowed to be extracted. For ^{220}Pa, the half-life of the ground state is measured to be 0.75(8) μs, which agrees with the value given in Refs. [1,3]. And for ^{216}Ac, the half-life is 0.35(5) ms. That value is in agreement with the literature data given in Ref. [7]. The half-life for the unknown α decay labeled by the blue color in Fig. 1(a) is deduced to be 233^{+108}_{-56} ns.

It should be noted that the time and position correlations between α decays can act as a very sensitive selection tool experimentally, particularly when one of the α decays has a short half-life. Consequently, it is reasonable to assume that the new α decay should originate from another excited state in ^{220}Pa. Furthermore there were no other decay chain patterns found in the region that could have similar decay properties to that one.

The reduced α widths for the ground states of the $N = 129$ isotones are shown in Fig. 4. They were calculated according to the prescription proposed by Rasmussen [11]. Using the new energy and lifetime values and assuming $\Delta L = 0$, the calculated α width for ^{220}Pa fits well into the systematics.

Although it is difficult to draw a definite conclusion, the spin-parity assignment to the newly observed 233-ns state in ^{220}Pa needs to be briefly discussed. Above the double-shell closure at $Z = 82$ and $N = 126$, α-decaying isomers

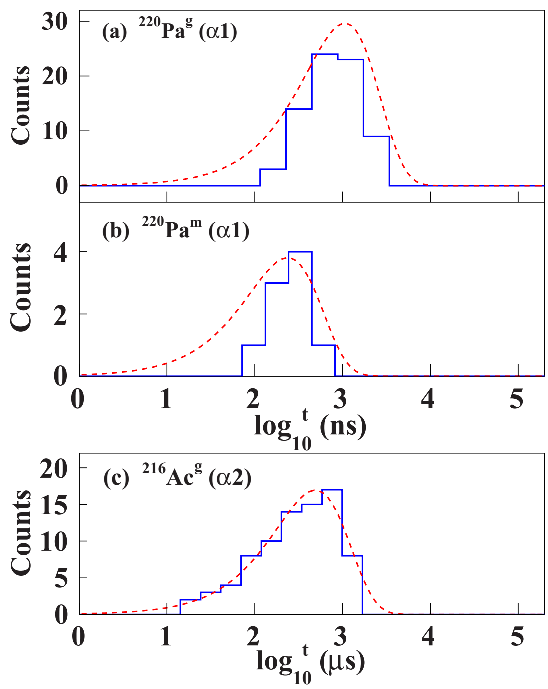

FIG. 3. The distributions of time differences between successive events in the PSSDs. Panels (a) and (b) show the time differences between the implanted recoil (ER) and the first decay (α1). Panel (c) shows the time differences between the first decay (α1) and the second decay (α2). The dotted lines are fitted decay curves as defined in Ref. [9].

systematically occur in many odd-odd isotopes. In the cases of odd-proton $N = 129$ isotones, two α-decaying isomers, namely (1^-) and (9^-) states mainly resulting from the coupling of the two single-particle orbits $\pi(h_{2/9})$ and $\upsilon(g_{9/2})$ have been found in ^{212}Bi [12], ^{214}At [13], and ^{216}Fr [14]. Nevertheless this pattern seems not to repeat itself in ^{218}Ac

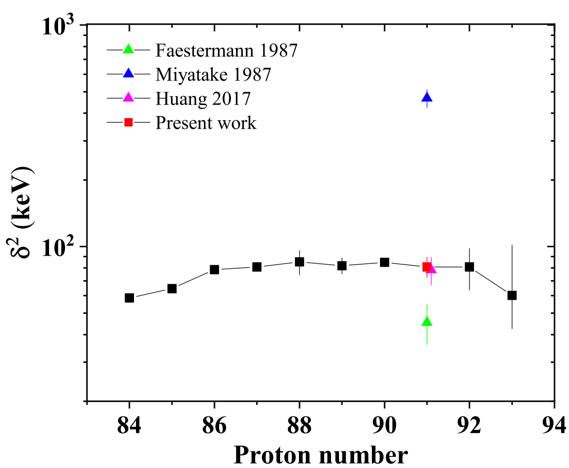

FIG. 4. Systematics of the reduced α widths for the $N = 129$. The black solid square refer to the δ^2 values were deduced from Refs. [5,12]. The red solid square refers to the value of ^{220}Pa measured in the present paper, compared to the values deduced from Faestermann *et al.* [1], Miyatake *et al.* [2], and Huang *et al.* [3].

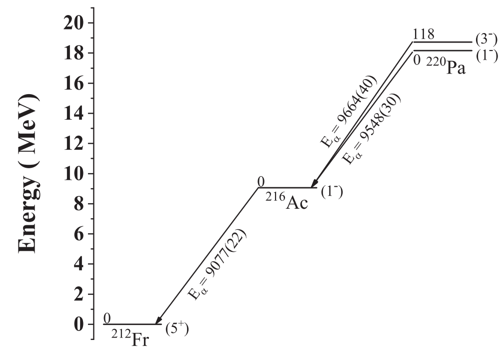

FIG. 5. Scheme of the α-decay chain from ^{220}Pa to ^{212}Fr resulting from the current paper α-decay energies, and energies of excited levels are in keV.

[15]. Although a band was built on a (9^-) state of unknown excitation energy [16], no α transition from the state was reported. However, the (3^-) state ([rising from the same origin of the (1^- or 9^-) state] has also come down with increasing Z number and becomes a 71-ns isomer in ^{216}Fr [17]. When moving up in proton number to the heavier isotones, this isomeric state would be expected to be lower lying and its α-emitting character could be more competitive. In the present paper, the newly observed 9664-keV α group from ^{220}Pa is in coincidence with the ground-state α line of ^{216}Ac. The spin difference between the proposed (1^-) ground state of ^{216}Ac and the new state in ^{220}Pa should not be large since there is no evidence for other transitions and since the α strength is concentrated into one dominant transition for each excited state. Hence the new 233-ns isomeric state should have a low spin, and the spin-parity of (3^-) might be tentatively assigned to it. According to the above discussions, the provisional decay scheme proposed by this paper is then presented in Fig. 5.

In Fig. 1, it can also be seen that there are few low-energy events (four events) seemly corresponding to the α ray of 9.160 (55) MeV reported by Miyatake *et al.* [2]. For the parent activity, the α energy and half-life were deduced to be $E_\alpha = 9160(30)$ keV and $T_{1/2} = 734^{+734}_{-245}$ ns, respectively. The standard deviation $\sigma_{\theta\,\mathrm{exp}}$ is calculated to be 1.28, which lies within the limits of the 90% confidence interval (0.31 and 1.92) for a data set of four events. In the meantime, the deduced daughter decay characteristics of $E_\alpha = 9063(30)$ keV and $T_{1/2} = 537^{+537}_{-179}$ μs is in agreement with the reported data of ^{216}Ac within error bars. From this view of point, the low-energy α-line mentioned above agrees with that reported by Miyatake *et al.* [2] and might come from ^{220}Pa. However, the $\sigma_{\theta\,\mathrm{exp}}$ is calculated to be 3.86 for daughter events, which is two times larger than the upper limit of 1.92 for a data set of four events. In this respect, the situation seems somewhat ambiguous. More detailed studies are necessary to make an unambiguous assignment for the 9.160-MeV α line. Above the 9664 (40)-keV α group, it can also be noted that few events mainly around 9760 keV exist. Two such correlated events [$\alpha1$ ($\approx$9760 keV) $\rightarrow$ $\alpha2$ ($\approx$9070 keV)] were also observed in the ^{40}Ar + ^{186}W reaction, which was for an internal calibration of PSSDs in the current experiment. The known isotope ^{221}U for which the decay properties of $E_\alpha = 9.71(5)$ MeV and $T_{1/2} = 0.66(14)$ μs have been reported in Ref. [18], was observed in that reaction. Thus, it was assumed that two events around 9760 keV observed in the ^{40}Ar + ^{186}W reaction would be false correlations and might be caused by the isotope ^{221}U. In the ^{40}Ar + ^{187}Re reaction, ^{221}U was not observed yet. Even so, the similar correlated events were still observed. It then becomes a puzzled question what could be their potential origin.

IV. SUMMARY

To summarize, we have reinvestigated the α-decay chain from ^{220}Pa to ^{216}Ac. Following implantation into PSSDs at the focal plane of the SHANS recoil separator, position and time correlations have been applied to identify 82 events in the $^{220}\text{Pa} \rightarrow {}^{216}\text{Ac}$ double α-decay chain. The energy for the ground state of ^{220}Pa has been measured to be 9548(30) keV, which agrees with the previously measured value [3]. The half-life of $^{220}\text{Pa}^g$ has been measured to be 0.75(8) μs, consistent with the previous measurement. Additionally, in the present paper a new isomeric state with an energy $E_\alpha = 9664(40)$ keV and with a half-life $T_{1/2} = 233^{+108}_{-56}$ ns has been observed in ^{220}Pa. Referring to the known low-lying states of the well-studied odd-proton $N = 129$ isotones, the spin parity of the new 233-ns isomer is tentatively suggested to be (3^-).

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