New Insights into the ^{243}Am + ^{48}Ca Reaction Products Previously Observed in the Experiments on Elements 113, 115, and 117

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(Received 4 October 2011; published 12 January 2012)

Results of a new series of experiments on the study of production cross sections and decay properties of the isotopes of element 115 in the reaction ^{243}Am + ^{48}Ca are presented. Twenty-one new decay chains originating from ^{288}115 were established as the product of the 3n-evaporation channel by measuring the excitation function at three excitation energies of the compound nucleus ^{291}115. The decay properties of all newly observed nuclei are in full agreement with those we measured in 2003. At the lowest excitation energy $E^* = 33$ MeV, for the first time we registered the product of the 2n-evaporation channel, ^{289}115, which was also observed previously in the reaction ^{249}Bk + ^{48}Ca as the daughter nucleus of the decay of ^{293}117. The maximum cross section for the production of ^{288}115 is found to be 8.5 pb at $E^* \approx 36$ MeV.

DOI: 10.1103/PhysRevLett.108.022502 PACS numbers: 27.90.+b, 23.60.+e, 25.70.Gh

The identification of new elements and their illumination of our understanding of the evolution of nuclear structure as one approaches the predicted spherical closed shells of $Z = 114$ (or 120 or 126) and $N = 184$ are major driving forces for studies of the heaviest atomic nuclei. Element 115 was observed for the first time in the reaction ^{243}Am + ^{48}Ca in 2003 [1,2]. At the projectile energy 248 MeV, three decay chains originating from ^{288}115 were registered. In all three cases, we detected consecutive α decays of ^{284}113, ^{280}Rg, ^{276}Mt, and ^{272}Bh terminated by the spontaneous fission (SF) of ^{268}Db or its electron-capture product ^{268}Rf. At 5 MeV higher ^{48}Ca energy, one decay chain of the isotope ^{287}115, product of the 4n-evaporation channel, was registered. Again, five sequential α decays of the isotopes ^{287}115, ^{283}113, ^{279}Rg, ^{275}Mt, ^{271}Bh (missing α particle) ended in the spontaneous fission of ^{267}Db. In total, eleven neutron-rich nuclei with an odd number of protons including two new elements with $Z = 115$ and 113 were produced in these experiments.

The synthesis of odd-Z superheavy nuclei provides more detailed information than even-Z nuclei about the nuclear structure of these nuclides because of their long decay chains. Even though the neighboring even-even nuclei undergo spontaneous fission, nuclei with an odd number of protons or neutrons may undergo α decay because of a strong fission hindrance caused by the unpaired nucleon. Thus, spontaneous fission occurs later in the decay sequence of such nuclei.

In theory, a relatively high stability against the spontaneous fission of the α-decaying isotopes of element 115 is caused by the strong influence of spherical nuclear shells at Z and N noted above (see, e.g., Ref. [3]). The five sequential α decays of the isotopes ^{287}115 and ^{288}115 lead to ^{267}Db ($N = 162$) and ^{268}Db ($N = 163$) that are already located in the vicinity of other nuclear shells at $Z = 108$ and $N = 162$ that are expected to be characterized by a relatively large deformation of the nuclei in their ground states. Such a transition in the course of consecutive α decays from presumably spherical to deformed nuclei possessing a larger variety of low-lying levels could be manifested in the structure of the energy spectra of the α particles. However, in order to observe this one needs to collect higher statistics.

We have measured the excitation functions of the xn-evaporation channels in the reaction ^{243}Am + ^{48}Ca; in so doing, we have produced and detected a large number of atoms of ^{288}115 and its decay daughters. Additionally, at the low energies close to the Coulomb barrier of the reaction we could expect to detect a heavier isotope, ^{289}115, that is also of great interest for us. Recently we produced this nucleus as the α decay daughter of the odd-even isotope of element 117 that was formed in the reaction ^{249}Bk(^{48}Ca, 4n) and decayed following the short chain: $^{293}117 \rightarrow {}^{289}115 \rightarrow {}^{285}113 \rightarrow {}^{281}$Rg (SF) [4,5]. Observation of the decay of ^{289}115 in the reaction ^{243}Am(^{48}Ca, 2n) with the corresponding energies and lifetimes of α decay and

TABLE I. Target thicknesses corresponding to ^{243}Am isotope quantity, lab-frame beam energies in the middle of the target layers, excitation energy intervals, total beam doses, and numbers of observed decay chains (N_{ev}) assigned to the parent nuclei $115^{288}/^{289}115$.

Target thickness (mg/cm^2)	E_{lab} (MeV)	E^* (MeV)	Beam dose $\times 10^{18}$	N_{ev} ($115^{288}/^{289}115$)
0.37	248.1	38.0–42.3	3.7	3/0
0.37	243.4	34.0–38.3	3.3	6/0
0.37	239.8	31.1–35.3	11.7	7/0
0.84	240.5	31.4–36.2	4.8	5/1

spontaneous fission would establish a direct connection between the two reactions and identify independently the genetically linked odd-even isotopes of elements 115 and 117 with neutron number 174 and 176, respectively. In this Letter we report 21 events originating from ^{288}115 (whose measured excitation function establishes these events are from the $3n$ channel) and one from the ^{289}115 ($2n$ channel).

The experimental setup is analogous to that used in our previous experiments [1,2,4,5]. The ^{48}Ca ion beam intensity of about 1 particle μA was obtained with the U400 cyclotron of the Flerov Laboratory of Nuclear Reactions, JINR.

We used the $36-\mathrm{cm}^2$ rotating targets of ^{243}Am (99.92%) deposited onto 1.5-μm Ti foils. The evaporation residues (ER) recoiling from the target were separated in flight from ^{48}Ca beam ions, scattered particles, and transfer-reaction products by the Dubna gas-filled recoil separator. The transmission efficiency of the separator for $Z = 115$ nuclei is estimated to be approximately 35% [1,2]. ERs passed through a time-of-flight system and were implanted in a 4 cm $\times$ 12 cm semiconductor detector array with 12 vertical position-sensitive strips surrounded by eight 4 cm $\times$ 4 cm side detectors without position sensitivity. The position-averaged detection efficiency for full-energy α particles emitted in the decays of implanted nuclei was 87%.

The experiments were performed with a few breaks between November 1, 2010 and March 31, 2011 at four beam energies. The corresponding excitation energies of the compound nucleus are given in Table I. In the two experiments at $E_{lab} \approx 240$ MeV we used different targets; the thicker one was prepared for subsequent experiments on the chemical identification of ^{268}Db [6].

The measured excitation function of the reaction $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$ is given in Fig. 1. Excitation energies of the compound nuclei are calculated using the masses found in [7,8]. When determining cross sections at $E^* = 33$ MeV in the experiments with the 0.84 mg/cm^2 target, we corrected the separator's transmission for increased scattering losses in the target. The cross section for the $3n$-evaporation channel at 40-MeV excitation energy was calculated taking into account results of the earlier experiment [1,2]. The cross section of the $3n$-evaporation channel reaches its maximum of $8.5^{+6.4}_{-3.7}$ pb at $E^* \approx 36$ MeV. The excitation function of the $^{243}\mathrm{Am}(^{48}\mathrm{Ca}, 3n)^{288}115$ reaction presented in Fig. 1 is in good agreement with the experimental cross sections $\sigma_{3n}(E^*)$ measured for the production of the neighboring nuclei ^{287}114 and ^{290}116 in the reactions of ^{242}Pu [9] and ^{245}Cm [10] with ^{48}Ca.

In addition to 21 new decay chains attributed to the parent nucleus ^{288}115, a short decay chain consisting of only two α decays and terminated by SF was observed at the lowest ^{48}Ca energy of 240 MeV. In this case, the ion beam was switched off after recording the signal of the recoil nucleus with $E_R = 11.4$ MeV and detection of a position-correlated α particle with $E_{\alpha 1} = 10.38$ MeV that followed in 0.26 s. In 1.4 s after switching the beam off, the focal-plane detector registered the second α particle with $E_{\alpha 2} = 9.89$ MeV and then, in about 2 s, followed the spontaneous fission signal with an amplitude of 216 MeV. Position deviations of all four signals associated with the recoil, i.e., ER implantation, two α particles, and a spontaneous fission, observed during 3.64 s in strip 3 indicated a strict correlation between these events ($\Delta P < 0.8$ mm). The number of such decays being simulated by chance coincidence in the same time interval and detector strip is 2×10^{-7} [11]. This decay chain, together with the long chains that characterize the average decay properties of ^{288}115 (24 events) and ^{293}117 (5 events), is presented in Fig. 2. From the comparison of the properties

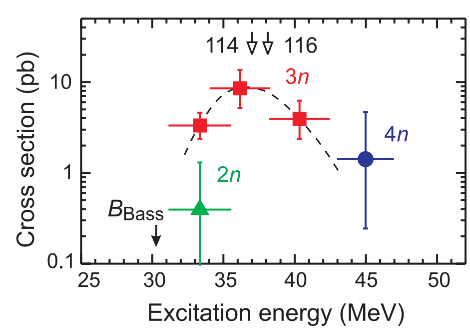

FIG. 1 (color). Cross sections for the $2n$, $3n$, and $4n$ evaporation channels of the reaction $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$. Vertical error bars correspond to statistical uncertainties [11]. Horizontal error bars represent the range of excitation energies populated for one beam energy. For reference purposes we show the energy at the Bass barrier [12] (black arrow). Open arrows represent excitation energies corresponding to the maxima of the $3n$-evaporation channel measured in the reactions $^{242}\mathrm{Pu} + {}^{48}\mathrm{Ca}$ [9] (left) and $^{245}\mathrm{Cm} + {}^{48}\mathrm{Ca}$ [10] (right). The dashed line through the $3n$ data is drawn to guide the eye.

of nuclei shown in Fig. 2 and the fact that the short $\alpha_1 \rightarrow \alpha_2 \rightarrow$ SF chain was detected only at the minimum excitation energy of the compound nucleus $^{291}115$ ($E^* \approx 33$ MeV), one can arrive at the conclusion that we have observed the decay of the neighboring isotope of element 115 with mass 289—the product of the $2n$-evaporation channel of the reaction $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$. Note that the products of the $2n$ channel of the reactions of the fusion of $^{242}\mathrm{Pu}$ and $^{245}\mathrm{Cm}$ with $^{48}\mathrm{Ca}$, the isotopes $^{288}114$ and $^{291}116$, were observed in our experiments with comparable cross sections at $E^* = 32$–33 MeV [9,10].

The α-particle energy spectra of the isotopes observed in the decay chains originating from the parent nucleus $^{288}115$ registered by the focal-plane detector in [1,2] and this work are summarized in Fig. 3 on the left-hand side. The decay-time distributions on a logarithmic scale for the same isotopes are given on the right-hand side of Fig. 3.

All 24 events due to the formation and decay of the nucleus $^{288}115$ as detected were consistent with chains of five sequential α transitions ending in spontaneous fission; there were some missing decays due to the detection efficiency of less than unity. Results of the three events in the first experiment, as indicated by the arrows in Fig. 3, are in good agreement with the data of the present work. The abnormally low energy of a single α particle of the mother nucleus $^{288}115$ (left-hand panel, upper plot) could be explained by the lack of full-energy deposition in the focal-plane detector even though the probability is low for this occurrence ($P_{\mathrm{err}} \sim 0.003$, $N_{\mathrm{err}} \sim 0.3$).

Despite the limited statistics of these decay chains, one can see multiline α-particle energy spectra for $^{288}115$, $^{280}\mathrm{Rg}$, $^{272}\mathrm{Bh}$ which can be partially explained by detection of conversion electrons in coincidence with α particles. An especially wide spectrum was observed for $^{276}\mathrm{Mt}$. At the same time, the α decay of $^{284}113$ looks like a transition from its one energy level to only one level of $^{280}\mathrm{Rg}$. Such a feature of the α-decay energy structure in this region of nuclei might be caused by theoretically predicted shape changes from oblate to prolate, or from superdeformed to low prolate shapes (see, e.g., [13,14]) in the course of consecutive α decays. Irrespective of the α-particle energy spectra, the nuclei in the decay chains are characterized in practically all cases by a single half-life as shown in the right-hand side of Fig. 3. The only exception is the decay of $^{276}\mathrm{Mt}$; here there are two α transitions which have the energies of 9.26 ± 0.64 MeV and 9.81 ± 0.08 MeV whose partial half-lives appear to be some 10 times higher than that associated with the rest of the decays.

In summary, in this work we have added 21 more new decay chains originating from $^{288}115$ which was discovered in 2003 [1,2] in the reaction $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$. Decay properties of all six nuclei synthesized in 2003 [1,2] and assigned to $^{288}115$, $^{284}113$, $^{280}\mathrm{Rg}$, $^{276}\mathrm{Mt}$, $^{272}\mathrm{Bh}$, and $^{268}\mathrm{Db}$ are in full agreement with those measured in the recent experiments with higher statistics. The measured excitation function of the reaction $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$ establishes that these events are the products of the $3n$-evaporation channel. Moreover, the isotope $^{289}115$ was synthesized in two cross bombardments using $Z = 97$ $^{249}\mathrm{Bk}$ and $Z = 95$ $^{243}\mathrm{Am}$ targets. Thus, these new data strongly support the discoveries of the elements 113 and 115. The cross section of the $3n$-evaporation channel is about 10 pb at

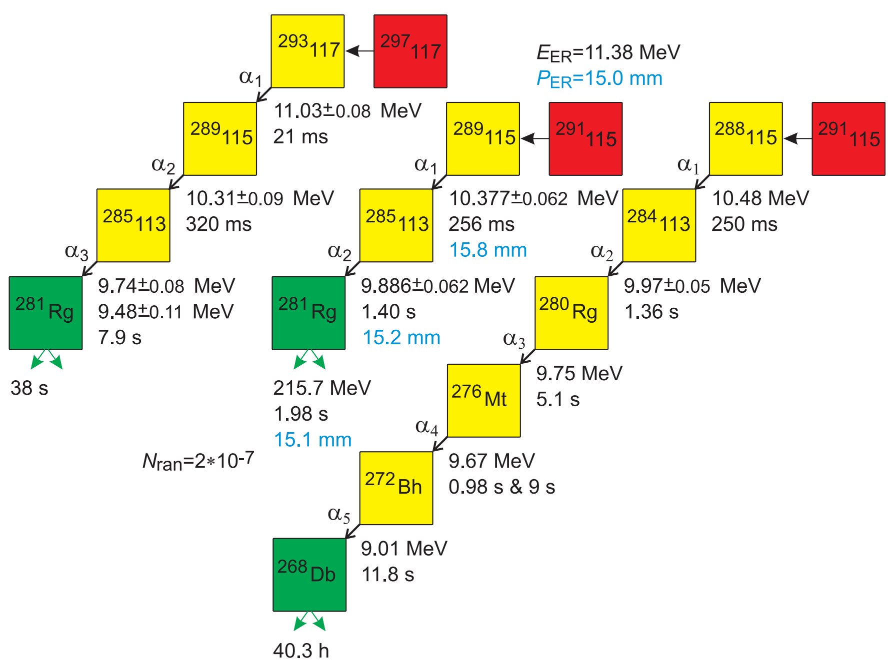

FIG. 2 (color). Observed decay chains interpreted as originating from the isotopes $^{293}117$ (average of five events) [4,5], $^{289}115$ (single event), and $^{288}115$ (average of 24 events—from 21 new and 3 prior decay chains). The measured α-particle energies (average values) and lifetimes are shown. For the $^{289}115$ decay chain positions of detected events are given in blue.

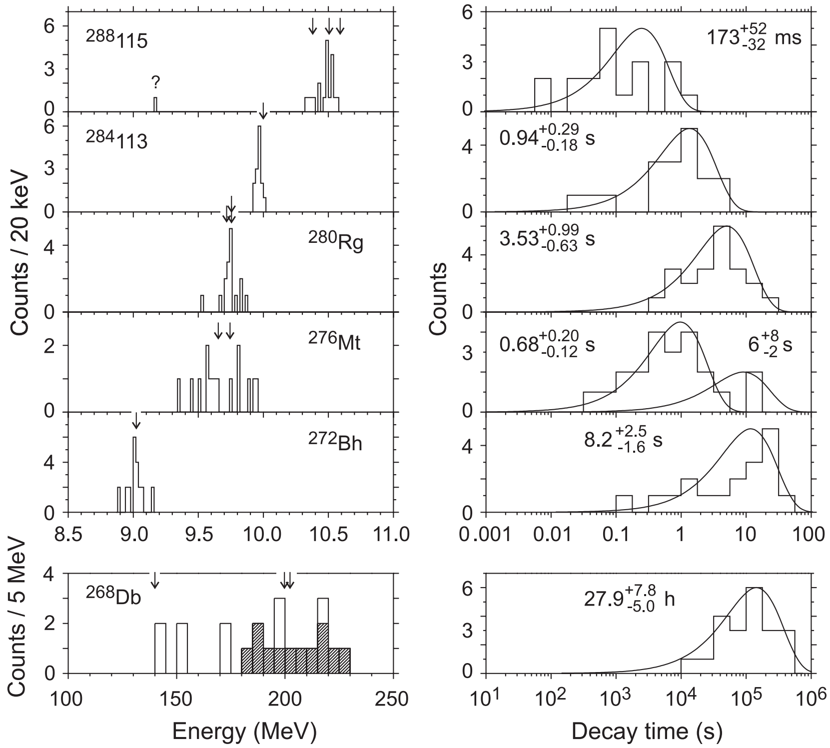

FIG. 3. α-particle and fission-fragment energy spectra registered by the focal-plane detector (left-hand panel) and decay-time distributions on a logarithmic scale (right-hand panel) for isotopes originating from $^{288}115$. The arrows show the energies of the three events obtained in the first experiment in 2003 [1,2]. The fission-fragment energies were not corrected for the pulse height defect of the detectors. SF events detected by only the focal-plane detector are shown by the open histogram; those detected by both focal-plane and side detectors, the shaded histogram. The smooth curves are the time spectra for exponential decays associated with the half-lives $T_{1/2}$ shown in the figures.

$E^* \approx 36$ MeV. The peak cross sections of the fusion-evaporation reactions $^{243}\mathrm{Am} + {}^{48}\mathrm{Ca}$ and $^{244}\mathrm{Pu} + {}^{48}\mathrm{Ca}$ [15,16] leading to elements 115 and 114 have the largest cross sections compared with those for other reactions where superheavy nuclei with lower or higher proton numbers were synthesized. The $^{289}115$ decay chain observed in this work is in agreement with the five chains previously reported in the reaction $^{249}\mathrm{Bk}(^{48}\mathrm{Ca}, 4n)$ as the descendant nucleus of the $^{293}117$ [4,5].

We are grateful to the JINR Directorate and U400 cyclotron and ion source crews for their continuous support of the experiment. We acknowledge the support of the Russian Foundation for Basic Research Grants No. 11-02-12050 and No. 11-02-12066. Research at ORNL was supported by the U.S. DOE Office of Nuclear Physics under DOE Contract No. DE-AC05-00OR22725 with UT-Battelle, LLC. Research at Lawrence Livermore National Laboratory was supported by LDRD Program Project No. 08-ERD-030, under DOE Contract No. DE-AC52-07NA27344 with Lawrence Livermore National Security, LLC. This work was also supported by the U.S. DOE through a Grant No. DE-FG-05-88ER40407 (Vanderbilt University). These studies were performed in the framework of the Russian Federation/U.S. Joint Coordinating Committee for Research on Fundamental Properties of Matter.

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