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Study of the properties of the superheavy nuclei Z = 117 produced in the ^{249}Bk + ^{48}Ca reaction

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Abstract. The reaction of ^{249}Bk with ^{48}Ca have been reinvestigated to provide new evidence for the discovery of element 117 on a larger number of events. The experiments were performed at five projectile energies and with a total beam dose of ^{48}Ca of about 4.6×10^{19}. Two isotopes ^{293,294}117 were synthesized in the ^{249}Bk+^{48}Ca reaction, providing excitation functions and α-decay spectra of the produced isotopes that establishes these nuclei to be the products of the 4*n*- and 3*n*-evaporation channels, respectively. Decay properties of ^{293,294}117 and of all the daughter products agree with the data of the experiment in which these nuclei were synthesized for the first time in 2010. The new ^{289}115 events, populated by α decay of ^{293}117, demonstrate the same decay properties as those observed for ^{289}115 produced in the ^{243}Am(^{48}Ca,2*n*) reaction thus providing cross-bombardment evidence. In addition, a single decay of ^{294}118 was observed from the reaction with ^{249}Cf – a result of the in-growth of ^{249}Cf in the ^{249}Bk target.

1 Introduction

Investigation of the radioactive properties of the superheavy elements and their formation cross sections in the reactions of complete fusion of actinide nuclei with ^{48}Ca ions provide important insights into understandings of the behavior of nuclear matter under extreme conditions of high *Z* and important tests of the prediction of an island of stability of superheavy nuclei. In the experiments performed with the Dubna gas-filled recoil separator (DGFRS) we have synthesized, for the first time, 9 isotopes of even-*Z* superheavy elements with atomic numbers 114 (Fl), 116 (Lv), and 118 in the reactions ^{242,244}Pu, ^{245,248}Cm, and ^{249}Cf+^{48}Ca (see [1] and references therein). The synthesis of odd-*Z*

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nuclei provides more detailed information than of even-*Z* nuclei about the nuclear structure of these nuclides because of their longer decay chains that result from strong fission hindrance caused by the unpaired nucleons. However, till 2012 the odd-*Z* nuclei were investigated in our experiments only[a]. For the first time the *Z*=115 nuclei and their decay products including *Z*=113 isotopes were observed in 2003 [2] and then in 2010-2012 [3] in the ^{243}Am+^{48}Ca reaction. In 2006 a lighter isotope ^{282}113 was synthesized in the ^{237}Np(^{48}Ca,3*n*) reaction [4]. The discovery of element 117 [5] has been reported using the ^{249}Bk+^{48}Ca reaction in 2009–2010. A relatively high stability of all these odd-*Z* activities is caused by the influence of presumably spherical nuclear shells at *Z*=114–126 and *N*=184.

In 2012, we have performed a new series of experiments to obtain more detailed information on the decay properties of odd-*Z* nuclei, to measure the excitation function of the ^{249}Bk+^{48}Ca reaction in a more extended range of projectile energies, and to make a cross-bombardment consistency check on the reported discoveries of element 117 [6].

2 Experiment

For the synthesis and identification of these odd-*Z* nuclei, we used the Dubna gas-filled recoil separator that selects only complete-fusion-evaporation reaction products which are strongly forward peaked and suppresses the yield of transfer reactions and reactions with emission of charge particles (*pxn*, α*xn*, etc.). The evaporation residues were separated with an estimated transmission efficiency for *Z*= 117 nuclei of about 35%, then passed through a time-of-flight system and implanted in a silicon detector. In the study of element 117, the detection system was modified to increase the position granularity of the detectors, which reduces the probability of observing sequences of random events that mimic decay chains of synthesized nuclei. The new focal-plane detectors consisted of two 6×6 cm^2 detectors each having 16 strips surrounded by six 6×6 cm^2 side detectors. Other experimental conditions were the same as in [1-5] (see Table 1). In order to reduce the background rate in the detector, the beam was switched off after a recoil signal was followed by an α-like signal in the focal-plane detector within energy and time intervals corresponding to decays of parent and/or daughter nuclei, in the same strip and close position.

Table 1. The ^{249}Bk target thickness[b], lab-frame beam energies in the middle of the target layers, resulting excitation-energy intervals, total beam doses, and numbers of observed decay chains assigned to the parent nuclei ^{293}117 (4*n*) and ^{294}117 (3*n*) are listed.

Target thickness (mg/cm^2)	E_{lab} (MeV)	E_{exc} (MeV)	Beam dose ×10^{18}	Number of chains 4*n* / 3*n*
0.33	243.7	30.4–34.7	9.4	0 / 1
–	246.8	32.8–37.5	3.4	0 / 2
–	251.7	37.0–41.9	11.7	5 / 0
–	255.7	40.3–44.8	9.2	3 / 0
–	259.8	43.8–48.3	11.9	3 / 0

3 Results

In the ^{243}Am+^{48}Ca reaction, at the lowest excitation energies *E**=31.1–36.4 MeV four decay chains of the isotope ^{289}115, product of the 2*n* channel, were observed [3]. Because of the mass difference

[a] See presentations by Ch.E. Düllmann and U. Forsberg at this Conference.
[b] As in [5], the ^{249}Bk was produced at ORNL at the High Flux Isotope Reactor. The Bk fraction was chemically separated and purified at the Radiochemical Engineering Development Center at ORNL. Six arc-shaped targets were made at RIAR.

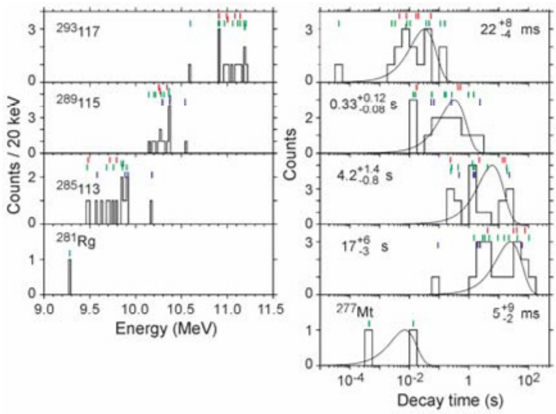

Figure 1. α-particle energy spectra registered by the focal-plane detector (left-hand panel) and decay-time distributions on a logarithmic scale (right-hand panel) for isotopes originating from ^{293}117. The events originating from ^{293}117 observed in the reactions with ^{249}Bk in the first experiment [5], in the second experiment [6], and in the reaction with ^{243}Am [3] are shown in the histograms by red, green, and blue lines, respectively.

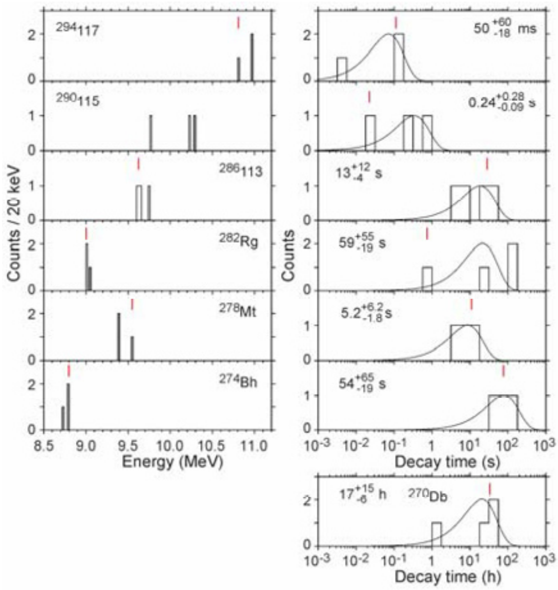

Figure 2. The same as Figure 1 but for ^{294}117. The vertical lines show the energies and decay times of the events obtained in the first experiment [5].

between ^{243}Am and ^{249}Bk (α+2n) and lower yields of the 1n and 5n channels than 2-4n channels, one and the same isotope of element 115, ^{289}115, can be produced only in the 2n- and 4n-evaporation channels of the ^{243}Am+^{48}Ca and ^{249}Bk+^{48}Ca reactions, respectively. Indeed, 11 decay chains of the parent isotope ^{293}117 were observed in the ^{249}Bk+^{48}Ca reaction at higher excitation energies E*=37.0–48.3 MeV. The radioactive decay properties of ^{293}117 and all the descendant nuclei discovered in 2010 [5] were confirmed by registration of 11 new decay chains in this new series of experiments [6]. One can see in Figure 1 that the characteristics of the five events in the first experiment [5] and four events originating from ^{289}115 and produced in cross reaction with ^{243}Am [3] are in good agreement with the recent data.

The heaviest isotope ^{294}117, product of the ^{249}Bk(^{48}Ca,3n) reaction, was synthesized at lower excitation energies of 30.4–37.5 MeV. The decay properties of all the nuclei determined in the four decay chains originating from parent nucleus ^{294}117 are shown in Figure 2. The properties of nuclei in the new decay chains point to the same activities arising from ^{294}117 detected in the two experiments using the ^{294}Bk target [5, 6].

The cross sections of the 3n and 4n evaporation channels at E*=35 and 39 MeV were measured to be $\sigma_{3n}=1.1^{+1.2}_{-0.6}$ pb and $\sigma_{4n}=1.5^{+1.1}_{-0.5}$ pb, respectively (see Figure 3). The maximum cross-section value of $2.4^{+3.3}_{-1.4}$ pb was measured for the 4n channel at E*=43 MeV.

The target isotope ^{249}Bk decays into ^{249}Cf with a half-life of 330 d. During a long experiment, this creates an opportunity to produce Z=118 isotopes in the ^{249}Cf+^{48}Ca reaction [7]. Indeed, with 247-MeV ^{48}Ca, we observed one more decay chain of nuclei whose radioactive properties agree well with those determined for ^{294}118 and its descendant nuclei ^{290}Lv and ^{286}Fl (fission branch of 50%) [1,7] (see Figure 4b). Taking into account the buildup of ^{249}Cf in the preceding [5] and present experiments, the detected decay chain of ^{294}118 corresponds to $0.3^{+0.7}_{-0.26}$ pb for the total excitation energy interval of 26.6–37.5 MeV for ^{297}118, in good agreement with cross sections measured in this reaction [1,7].

In conclusion, the discovery of the chemical elements with atomic numbers 113, 115, and 117 that were synthesized for the first time in 2003 [2] and 2010 [5] has now been corroborated through the observation of additional decay chains in the reaction ^{249}Bk+^{48}Ca. In total, 59 decay chains originating from odd-Z parent nuclei ^{282}113, $^{287–289}$115, and ^{293,294}117 were synthesized and radioactive decay properties of 29 new isotopes were determined (see Figure 4 a).

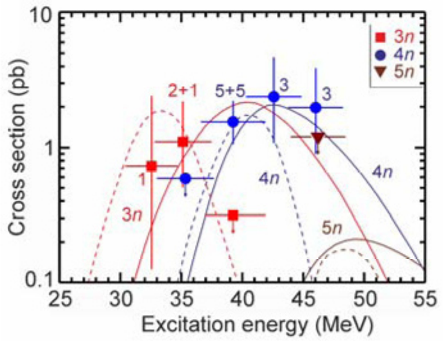

Figure 3. Measured cross sections for the 3*n* and 4*n* evaporation channels for the ^{249}Bk+^{48}Ca reaction. Vertical error bars correspond to statistical uncertainties [8]. Horizontal error bars represent the range of excitation energies populated at given beam energy. Symbols with arrows show upper cross-section limits. Numbers of detected decay chains are given for each ^{48}Ca energy. The results of theoretical calculations are shown by solid [9] and dashed [10] lines.

Acknowledgments

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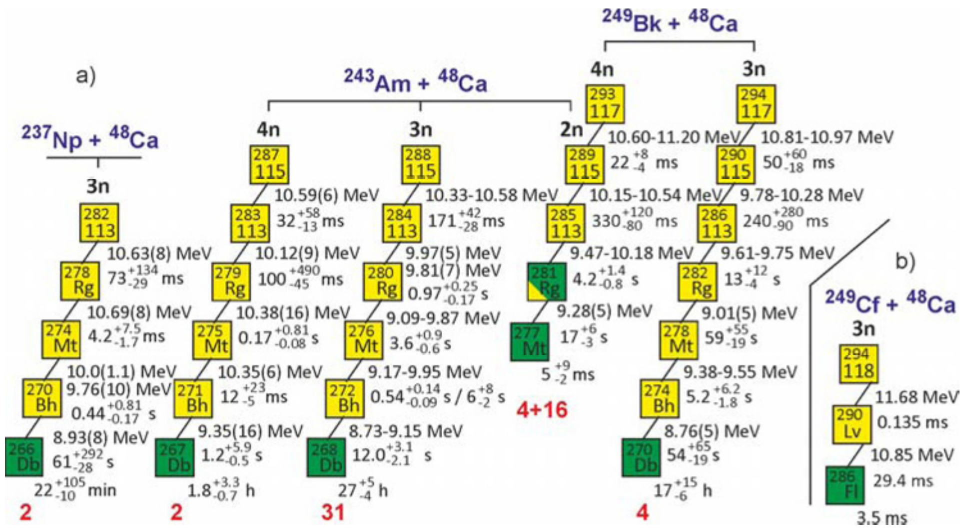

Figure 4. (a) Summary of the decay properties of the isotopes of elements 113, 115 and 117 observed for the first time among the reaction products of ^{48}Ca beam with ^{237}Np, ^{243}Am and ^{249}Bk targets. The number of the detected decay events of a given isotope is shown at the bottom of the chains. (b) Decay properties of ^{294}118–^{286}Fl measured in the ^{249}Cf(^{48}Ca,3*n*) reaction [6].

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