New data from the $^{243}$Am + $^{48}$Ca reaction give cross-bombardment verification of elements 113, 115 and 117

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Abstract The reaction $^{243}$Am + $^{48}$Ca has been reinvestigated to provide new evidence for the discovery of elements 113, 115. Twenty eight new $^{288}$115 decay chains were detected in this reaction to increase from three to 31 the number of $^{288}$115 atoms observed. In addition, four new decay chains were observed for the first time and assigned to the decay of $^{289}$115. These new $^{289}$115 events have the same properties for their decay chains as those observed for $^{289}$115 populated in the alpha decay of $^{293}$117 produced in the $^{249}$Bk + $^{48}$Ca reaction to provide cross-bombardment evidence. These new high statistics data sets and the cross-bombardment agreement provide definitive evidence for the discoveries of the new elements with $Z = 113, 115, 117$.

1. Introduction
The discovery of new higher $Z$ elements and the determination of their decay properties provide important insights into our understandings of the behaviour of nuclear matter under extreme conditions of high $Z$ and important tests of the prediction of an island of stability around $N = 184$ and high $Z$. Element 115 was seen for the first time in the reaction $^{243}$Am + $^{48}$Ca in 2003 [1, 2] along with the new element 113 populated by the alpha decay of element 115. In this reaction at a projectile energy of 248 MeV, three alpha decay chains $^{285}$115$\rightarrow ^{281}$113$\rightarrow ^{280}$Rg$\rightarrow ^{276}$Bh terminated by the spontaneous fission (SF) of $^{268}$Db or its electron-capture product $^{268}$Rf were observed. At 5 MeV higher bombarding energy, one equally long alpha decay chain, assigned to the 4n evaporation channel to $^{287}$115, was observed. Two isotopes of the new elements with $Z = 115$ and 113 along with nine new neutron-rich isotopes of known elements were observed in that experiment [1, 2].
These element 115 decay chains presumably go from spherical Z = 115 to deformed 287,288Db (N = 162,163) which are in the vicinity of expected shell gaps for deformed shapes for Z = 108, N = 162, as shown in Fig. 1. Such a shape transition could show up in the energies of the alpha particles to low energy excited levels in the deformed nuclei.

In the first stage of our new studies of the 243Am + 48Ca reaction, an excitation function was measured and twenty-one decay chains of 288115 were observed [3]. In addition, at the lowest energy, one new short decay chain was observed and was assigned to the 2n channel leading to 289115 [3]. It is important to clearly establish 289115 because it is the same isotope seen in the alpha decay of 293117 produced in the 249Bk + 48Ca reaction [4, 5], 293117 → 289115 → 285113 → 281Rg (SF). An important example of cross-bombardment verification of new elements is illustrated in Fig. 2 [6]. It is essential to determine that the decay chain of 289115 seen in the 243Am (48Ca, 2n) reaction has the same alpha energies and lifetimes as those of 289115 observed in the 249Bk + 48Ca reaction [4, 5]. Their agreement will provide a direct, cross-bombardment connection between the two reactions to independently verify new elements with Z=113, 115, and 117.

Thus the 248Am + 48Ca experiment was continued at the lowest energy. A total of seven additional 288115 chains were found to give an observed total of 31 decay chains of 288115. More importantly, three new decay chains were found for 289115 at the lowest energy. These four 289115 chains indeed have the same alpha energies and lifetimes as seen in the 289115 decay chains populated by alpha decay in the 249Bk reaction [4, 5] to give cross-bombardment verification of elements 113, 115, 117. At the highest energy one new event of 287115 was seen.
2. Experimental Details and Results

The same experimental set up as described in our recent letter [3] was used to continue the experiment. The target was 0.68 mg/cm² ²⁴³Am. The ⁴⁸Ca ion beam intensity was about 1 particle μA from the U 400 cyclotron of the Flerov Laboratory of Nuclear Reactions. The 99.52% ²⁴³Am target was rotated at 1700 RPM. The Dubna gas-filled recoil separator was used to separate the evaporation residues (ER) recoiling from the target from ⁴⁸Ca beam ions, scattered particles and transfer reaction products. After passing through a time-of-flight system, the ERs were implanted into a 4 cm x 12 cm semiconductor detector array with 12 vertical position sensitive strips surrounded by eight 4 cm x 4 cm side detectors without position sensitivity.

The second ²⁴³Am + ⁴⁸Ca experiment was carried out between November 2011 and February 2012 at two energies, 241 MeV, the same energy used at the end of the first experiment where one event of ²⁸⁸¹¹⁵ was observed and 254 MeV to observe the 4n evaporation channel to ²⁸⁷¹¹⁵ (see Table 1).

Table 1. Properties of the reaction of ²⁴³Am + ⁴⁸Ca. Three 3n and one 4n events were observed in the first report [1, 2]. There were no pxn reactions observed producing Fl (Z = 114) whose decay chains are known.

| Target Thickness (mg/cm²) | E_{lab} (MeV) | E_{exc} (MeV) | Beam dose x 10¹⁸ | Number of chains ²⁸⁷¹¹⁵/²⁸⁸¹¹⁵/²⁸⁹¹¹⁵ 4n/3n/2n |
|---------------------------|----------------|--------------|------------------|---------------------------------|
| 0.37                      | 248            | 38.0-42.3    | 3.7              | 0/3/0                           |
| 0.37                      | 243            | 34.0-38.3    | 3.3              | 0/6/0                           |
| 0.37                      | 240            | 31.1-35.3    | 11.7             | 0/7/0                           |
| 0.84                      | 241            | 31.4-36.2    | 4.8              | 0/5/1                           |
| 0.68                      | 241            | 32.0-36.4    | 5.6              | 0/7/3                           |
| 0.68                      | 254            | 42.5-47.2    | 4.4              | 1/0/0                           |

In general, in each case after a ER signal and an alpha signal with the expected energy in the same pixel, the beam was shut off and the subsequent alpha events and SF were seen with essentially no
The number of such short decays, representing $^{289}115$, being simulated by chance coincidence in the same time interval and detector strip, is of the order of $2 \times 10^{-7}$\cite{7}. The ER, alpha particles and SF events were found to occur in the same detector strip and vertical position within $\leq 2.3$ mm in each of the four events.

The properties of the two $^{243}$Am + $^{48}$Ca reaction experiments and the number of each type event are given in Table 1. The first four rows were reported earlier \cite{3}. The data from the continuation experiment are contained in the last two rows. A total of 31 decay chains of $^{288}115$, four decay chains of $^{289}115$ and two of $^{287}115$ are now observed. The 31 decay chains of $^{288}115$ provide the most accurate knowledge of alpha energies and half lives known for superheavy elements and their decay products. The maximum of the cross section, $8.5^{+4.4}_{-3.5}$ pb , is the largest measured for any of the $^{48}$Ca reactions. Note that the products of the 2n channel of the reactions of the fusion of $^{242}$Pu and $^{245}$Cm with $^{48}$Ca, the isotopes $^{288}114$ and $^{291}116$, were observed in experiments with comparable cross sections at $E = 32-33$ MeV \cite{8, 9}.

The four 2n (3 new and 1 old) evaporation channel reactions producing $^{289}115$ and the resulting decay chains are shown in Fig. 3. The short decay chains involve only two alpha emissions and then spontaneous fission. The alpha energies and lifetimes for both the four $^{289}115$ decay chains populated in the $^{243}$Am + $^{48}$Ca reaction \cite{3} and the five $^{289}115$ (now 10) chains populated by alpha decay of $^{293}117$ in the $^{249}$Bk + $^{48}$Ca reaction are shown as histograms in Fig. 4. The energies and lifetimes of the $^{289}115$ decay chains populated in the alpha decay of $^{291}117$ produced in the $^{249}$Bk + $^{48}$Ca reaction \cite{4, 5} are shown by arrows to illustrate the good agreement. Note that two of the daughter $^{289}115$ alphas were not detected in that experiment because of 87% alpha particle detection efficiency. There is excellent agreement between the two sets of data as seen in Fig. 4.

The cross-bombardment verification of the discoveries of elements 113, 115 and 117 are illustrated in Fig. 5. The $^{291}117$ decay chain alpha energies and lifetimes are averages of the first $^{249}$Bk + $^{48}$Ca experiment \cite{4, 5} which may be compared with the lifetimes of the four decay chains from $^{289}115$ populated in the $^{243}$Am reaction, 520 ms, 4.5 s and 11 s. The averages of the two sets of data are shown in Fig. 4. Note, since the conference was held, we now have observed five additional $^{293}117$.
decay chains in our current $^{249}$Bk + $^{48}$Ca experiment, with the alpha decay of $^{289}$115 now seen in each of these chains. These new decay chains are in agreement with our first experiment [4, 5]. So with ten $^{293}$117 decay chains, we have even better statistical verification of the new elements.

Fig. 4. The alpha energies and lifetimes for the decay chains originating with $^{289}$115 in the reaction $^{243}$Am + $^{48}$Ca and for the alpha decay to $^{289}$115 from $^{293}$117 in the reaction $^{249}$Bk + $^{48}$Ca. The histogram data include both Bk and Am results. In the $^{285}$113 alpha energy histogram, there are three events at 9.48, 9.51 (117 experiment) and 9.58 MeV (115 experiment). The arrows are data from 117 [4, 5].

Fig. 5. Cross-bombardment verifications of the new elements 117, 115 and 113 in the reactions shown. The original $^{288}$115 energies and lifetimes are given in Fig. 5 [1, 2]. These compare favorably with lifetimes of 170 ms, 0.7 s, 3.6 s, 0.54/6 s, 12 s and 26 h for the 31 decay chains beginning at $^{288}$115.
3. Summary
Summarizing, 28 more new decay chains were observed originating from $^{288}$115 which was discovered in 2003 [1, 2] in the reaction $^{243}$Am + $^{48}$Ca. Decay properties of all nuclei in the three decay chains synthesized in 2003 are in full agreement with those measured in our two recent experiments with higher statistics. The measured excitation function of the reaction $^{243}$Am + $^{48}$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 $Z = 97$ $^{249}$Bk and $Z = 95$ $^{243}$Am targets. Four new decay chains of $^{289}$115 were found in the $^{243}$Am + $^{48}$Ca reaction. These decay chain data are in full agreement with the data for $^{289}$115 populated via alpha decay of $^{293}$117 in the $^{249}$Bk + $^{48}$Ca reaction. These new cross-bombardment data give strong additional support to the discoveries of the elements 113, 115 and 117.

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