Discoveries of Elements 113, 115 and 117

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Abstract. Discovery of two isotopes of the new element 117 in the $^{249}$Bk + $^{48}$Ca reaction is described. A new $^{243}$Am + $^{48}$Ca experiment was carried out to firmly establish the discoveries of new elements 115 and 113. A total of thirty one decay chains of $^{288}$115 are now observed in the Am reaction. In addition, four new decay chains are assigned to $^{289}$115.

Introduction

One of the important frontiers in nuclear research is the discovery of new elements in the Periodic Table and their decay properties. These studies probe nuclear matter under extreme conditions of the Coulomb force at high Z and test nuclear structure predictions of proton and neutron shell closures under such extremes. An Island of Stability is predicted for N = 184 and Z between 114 and 126.

The discoveries of new elements 113, 114, 115, 116 and 118 were reported by bombarding actinide targets up through $^{249}$Cf with $^{48}$Ca [see ref. 1] [see Fig. 1]. The element 117 was missing because the necessary target, $^{249}$Bk, is so short-lived it must be produced in a high flux reactor shortly before the experiment. Beginning in 2005, scientists from the Joint Institute for Nuclear Research in Dubna and Vanderbilt University began discussions with scientists at the High Flux Isotope Reactor, HFIR, to obtain a target of $^{249}$Bk. When the possibility of obtaining $^{249}$Bk from a reactor irradiation in progress at HFIR became known, a meeting was held at Vanderbilt in 2008 between JINR, ORNL and Vanderbilt scientists to plan a cooperation to obtain and use $^{249}$Bk as a target to identify the new element 117. Lawrence Livermore National Laboratory scientists were subsequently invited to join the collaboration. The $^{249}$Bk + $^{48}$Ca reaction was studied in 2009-10. Five decay chains associated with $^{293}$117 were identified along with one longer decay chain assigned to $^{284}$117 [2, 3].

Earlier, the reaction $^{243}$Am + $^{48}$Ca was used to identify the new elements 115 and 113 [4, 5]. In that work, three decay chains were assigned to $^{288}$115 and one to $^{287}$115. To more definitely establish the $^{288,287}$115 decay chains, this experiment was repeated. In the first part of the experiment, 21 new decay chains of $^{288}$115 were identified at four different energies to give an excitation function. At the lowest bombarding energy, one new decay chain was observed and assigned to the 2n evaporation channel to $^{289}$115 [6]. This new $^{289}$115 is an important discovery because it is also populated in the
alpha decay of $^{293}$117 in the Bk reaction to give cross-bombardment verification of these three new elements.

Figure 1. Chart of Nuclides. Shown in yellow are the new elements and isotopes produced in reactions of $^{48}$Ca with actinide target. Element 117 is missing.

Experimental Procedures and Results
Details of the procedures and results are found in refs. 2, 3. Here is a brief summary. The $^{249}$Bk was produced in the HFIR by irradiating Cm and Am targets for approximately 250 days by a thermal neutron flux of $2.5 \times 10^{15}$ n/cm$^2$/s. After a three month waiting period to allow the short-lived activities to decay, the $^{249}$Bk was chemically separated from the other actinides over a three month period. The procedures were described earlier [2, 3]. The 22 mg of purified $^{249}$Bk was shipped to Russia where it was put into a circular target ring at the Research Institute of Atomic Reactors. The $^{249}$Bk material thickness was 0.31 mg/cm$^2$. The wheel was rotated at 1700 rpm to minimize the heating of the target.

The target was bombarded with $^{48}$Ca from the U400 cyclotron at the Flerov Laboratory for Nuclear Reactions. The target was irradiated with a $^{48}$Ca beam dose of $2.4 \times 10^{19}$ particles over 70
days at an excitation energy of 39 MeV for the reaction. The energy was then lowered to an excitation energy of 35 MeV and the target irradiated with a beam dose of $1.7 \times 10^{18}$ $^{48}$Ca particles for 60 days.

The evaporation residues were separated from the $^{40}$Ca beam particles, scattered particles and transfer reaction products by the Dubna gas-filled recoil separator. After passing through two time-of-flight detectors to insure the ERs were from the separator, the ERs were implanted into a $4 \times 12$ cm$^2$ semiconductor with 12 position sensitive strips surrounded by eight $4 \times 4$ cm$^2$ side detectors with no position sensitivity. The uncertainties in the energies of alpha particles detected only in the side detectors was the order of 0.4 MeV. The ERs, alphas and spontaneous fission events all were required to be in the same pixel with all the events in $\leq 1$ mm full width and half maximum. The registration efficiency for alpha particles was 87% and for a single fission fragment 100%.

As shown in Fig. 2, when an ER with an energy in the right range followed by an alpha particle in the same pixel ($\leq 1$ mm) and with the expected energy and half life for the 117 isotope, the beam was cut off and the subsequent alpha decays and SF were observed with very low background.

**Figure 2.** Low background detection where the beam is cut off after the right ER and first alpha decay observed within pre-selected ranges as shown.

At an excitation energy of 39 MeV, five decay chains of $^{293}$117 were observed and at $E^* = 35$ MeV, one long chain of six alphas followed by SF for the decay of $^{294}$117. These results are shown in Fig. 3 [2, 3]. Note the good agreement of the experimental alpha energies and lifetimes shown in black with the theoretical ones [7] shown is blue below the experimental ones. Note for $^{294}$117, since only one event was observed, lifetimes were estimated from the decay times for each alpha decay. The systematics of the known and our new alpha energies and half lives are shown in Fig. 4. Note all the half lives of our 11 new isotopes are significantly longer than those previously known for elements 111 to 115 because their extra one to two neutrons make these isotopes closer to $N = 184$. Thus, these data give strong support for the predicted Island of Stability around $N = 184$. Note $^{294}$117 ($N = 177$), the most neutron-rich isotope observed, has $T_{1/2} \approx 78$ ms while $^{294}$118 ($N = 176$) with only one less neutron has a half life of only 0.9 ms.
By using the same experimental procedures as in the 117 work [2, 3] and earlier 115 work [4, 5], the $^{243}$Am + $^{48}$Ca experiment was repeated at five energies, from $^{48}$Ca 240 to 253 MeV, over a period of many months in 2011-2012. Beam doses of 3.3 to $11.7 \times 10^{18}$ particles were achieved at each of the five energies. In the first experiment, a total of 21 new decay chains of $^{288}$115 and at the lowest energy, one new event assigned to the new isotope $^{289}$115 were observed as shown in Fig. 5 [6]. These 21 new decay chains are in full agreement in terms of alpha energies and half lives with the three chains reported earlier [4, 5]. The experiment was continued and seven additional decay chains of $^{288}$115, three additional ones of $^{289}$115 and one of $^{287}$115 [8] were observed. These 31 decay chains of $^{288}$115 are the largest number of events providing the most accurate known alpha energies and lifetimes of any superheavy element above $Z = 110$. The four new $^{289}$115 decay chains are extremely important because they are the same chains seen in the decay of $^{289}$115 populated in the alpha decay of $^{293}$117 produced in the $^{249}$Bk + $^{48}$Ca reaction. Thus these $^{289}$115 data from the Bk and Am reactions provide cross-bombardment verification of the new elements 117, 115 and 113. Since the end of the conference, five additional $^{293}$117 and three additional $^{294}$117 decay chains have been observed.

![Figure 3](image.png)

**Figure 3.** The averages of the five decay chains of $^{293}$117 and the one long chain seen in $^{294}$117 decay from the $^{249}$Bk + $^{48}$Ca are shown [2, 3]. Note the good agreement of the macroscopic-microscopic calculated alpha energies (blue) and our experimental ones (black). Figure taken from Ref. [2].
Figure 4. Alpha decay energies and half lives of known and new isotopes from the decays of $^{293,294}_{117}$. The new data are in red. All the half lives of our 11 new isotopes because they are one or two neutrons closer to $N = 184$ to support its magic character. Figure taken from Ref. [2].

Figure 5. Examples of the 21 new $^{288}_{115}$ decay chains and one new $^{289}_{115}$ decay chains seen in $^{243}_{95}$Am + $^{48}_{20}$Ca reaction [6]. Figure adapted from Ref. [6].

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