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Actinide targets for the synthesis of super-heavy elements ☆

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Abstract

Since 2000, six new super-heavy elements with atomic numbers 113 through 118 have been synthesized in hot fusion reactions of ^{48}Ca beams on actinide targets. These target materials, including ^{242}Pu, ^{244}Pu, ^{243}Am, ^{245}Cm, ^{248}Cm, ^{249}Cf, and ^{249}Bk, are available in very limited quantities and require specialized production and processing facilities resident in only a few research centers worldwide. This report describes the production and chemical processing of heavy actinide materials for super-heavy element research, current availabilities of these materials, and related target fabrication techniques. The impact of actinide materials in super-heavy element discovery is reviewed, and strategies for enhancing the production of rare actinides including ^{249}Bk, ^{251}Cf, and ^{254}Es are described.

Keywords: Actinide; Actinide target; Super-heavy element; Berkelium; Californium; Einsteinium

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Table 1
Hot fusion reactions using actinide + ^{48}Ca reactions have been used to produce six new super-heavy elements since 2000. The results were originally obtained at Dubna with later confirmations at GSI and LBNL (114), and GSI (115, 116, 117). Shown is the number of nuclei directly produced as well the total production including nuclei observed in decay chains.

Element (Z)	Year	Target	Projectile	Nuclei produced (directly/total)	Reference
(113)	2004	^{243}Am	^{48}Ca	2/89	[25,32]
Flerovium (114)	2000	^{244}Pu	^{48}Ca	64/99	[24,30,31]
(115)	2004	^{243}Am	^{48}Ca	63/87	[25,32]
Livermorium (116)	2005	^{245,248}Cm	^{48}Ca	31/35	[26,33]
(117)	2010	^{249}Bk	^{48}Ca	22	[28,34,46]
(118)	2006	^{249}Cf	^{48}Ca	4	[27]

1. Introduction

Actinides are radioactive elements ranging from atomic number 89 through 103. First identified as a new row in the Periodic Table by Seaborg in the 1940s [1,2], most actinides are highly reactive metals with a wide range of valence states and physical properties. Thorium and uranium are the only actinides that occur in substantial quantities in nature. Actinium and protactinium were discovered around 1900 as decay products in uranium ores [3].

All actinides heavier than uranium were discovered using other actinides as targets. Neptunium (1940), plutonium (1941), americium (1944), curium (1944), berkelium (1949), and californium (1950) were first produced at the University of California, Berkeley using accelerator-based nuclear reactions with neutrons, deuterons, and alpha particles on actinide targets [4]. Einsteinium and fermium were first isolated at Berkeley in 1952 from the products of neutron irradiation of uranium in a nuclear explosion [5]. Mendelevium (1955), nobelium (1965), and lawrencium (1961–1965) were first produced in accelerators at Berkeley [6], the Joint Institute for Nuclear Research, Dubna [7,8], and Berkeley [9] and Dubna [10], respectively, all using actinide targets. Synthetic production in nuclear reactors is required to accumulate more than trace quantities of actinides heavier than uranium, with only neptunium, plutonium, americium, curium, berkelium, and californium available in the quantities (∼10 mg) needed for targets for super-heavy element synthesis.

Super-heavy elements are elements with atomic numbers of 104 or greater. Nine of the 15 super-heavy elements synthesized to date have been produced using actinide targets. The first super-heavy element, rutherfordium (Z = 104), was originally observed [11] at Dubna in 1964 using accelerator irradiation of a plutonium target with neon ions, with further work [12,13] at Dubna and Berkeley leading to formal acceptance as a new element. Dubnium (Z = 105) was produced [14,15] contemporaneously at Berkeley and Dubna in 1970, from nitrogen on californium and neon on americium, respectively. Berkeley used oxygen beams on californium to produce seaborgium (Z = 106) [16] in 1974 with contemporaneous work at Dubna [17]. From 1981–1996, super-heavy elements Z = 107–112 were first produced at GSI, Darmstadt using non-actinide lead and bismuth targets in cold fusion reactions [18–23].

Since 2000, six new elements with atomic numbers Z = 113–118 have been produced [24–28] using the "hot fusion" technique [29], where neutron-rich actinide targets are bombarded by neutron-rich ^{48}Ca ions, as summarized in Table 1. These elements were first produced at Dubna, with later hot fusion experiments at Berkeley confirming element 114 [30] and GSI, Darmstadt confirming elements 114 [31], 115 [32], 116 [33] and 117 [34]. Successfully pioneered and de-

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