EXPERIMENTAL STUDY OF THE $^{249-251}Cf+^{48}Ca$ REACTIONS: TOWARD THE MAGIC NEUTRON NUMBER N=184

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Recently several complete-fusion reactions have been studied at the DGFRS setup (FLNR, JINR) with an aim of exploring the boundaries of the “Island of Stability” of the superheavy elements (nuclei around Z=114-126 and N=184). During the $^{249-251}Cf+^{48}Ca$ run with mixed Cf target (50.7% of ^{249}Cf, 12.9% of ^{250}Cf, and 36.4% of ^{251}Cf) just one decay chain was detected at the 252-MeV beam energy which was attributed to the previously observed ^{294}Og isotope, the product of the $^{249}Cf(^{48}Ca,3n)^{294}Og$ reaction; the corresponding reaction cross section was measured. For the $^{251}Cf(^{48}Ca, 3\text{-}4n)^{295,296}Og$ reactions no Og decays were detected during this run. Future possibilities for synthesis of new nuclides in the region of SHEs, namely more neutron-rich Lv, Ts and Og isotopes and new nuclides with higher Z (119 and 120), are discussed.

Keywords: Superheavy nuclei; alpha decay; compound nucleus, reaction cross section.

1. Introduction

The existence of an enhanced stability in the region of the superheavy nuclei, which has been developed in various theoretical approaches and hypothesized for about 50 years, has been validated by recent experiments. More than 50 new isotopes of the nuclei with Z = 104-118 from the predicted “Island of stability” of superheavy elements (SHE) were studied in pioneering experiments employing the Dubna Gas-Filled Recoil Separator (DGFRS), where performed complete-fusion reactions of ^{238}U, ^{237}Np, $^{242,\ 244}Pu$, ^{243}Am, $^{245,\ 248}Cm$, ^{249}Bk and ^{249}Cf targets with accelerated ^{48}Ca ions lead to the synthesis of the six new elements 113(Nh), 114(Fl), 115(Mc), 116(Lv), 117(Ts) and 118(Og) of the Periodic Table [1]. Also a few “hot fusion” reactions induced by ^{48}Ca ions and using actinide targets (^{238}U, ^{242,244}Pu, ^{243}Am, ^{248}Cm, and ^{249}Bk) were studied at IVO (FLNR, PSI), SHIP, TASCA (GSI), BGS (LBNL), and GARIS (RIKEN) setups then. Obtained there experimental data on isotopes ^{283}Cn, $^{285\text{-}289}$Fl, ^{287,288}Mc, $^{290\text{-}293}$Lv, and ^{294}Ts [2-7] are in full consistent with the results from DGFRS. Studied decay properties of these Z=112-118 nuclei point to a considerable stabilizing effect when approaching the predicted neutron magic number N=184.

There are few possible ways to expand our knowledge about more habitants from the SHE region. Since the isotopes of $^{249\text{-}251}$Cf are the heaviest material available in enough quantities for target production today, one can try to go further to higher Z of new elements in direct reactions with heavier than ^{48}Ca projectiles bombarding U – Cf targets. Five reactions ^{64}Ni + ^{238}U (SHIP [8]), ^{58}Fe + ^{244}Pu (DGFRS [9]), ^{54}Cr + ^{248}Cm (SHIP [8]), ^{50}Ti + ^{249}Cf and ^{50}Ti + ^{249}Bk (TASCA [10]) leading to $^{299,302}120^{*}$ and $^{299}119^{*}$compound nuclei were employed already, however, no events attributed to SHE were observed in these experiments. The upper cross section limits were set at 0.07 – 1.1 pb range depending on the reaction. Obviously, the sensitivities of present experiments are not enough and new modern facilities (like Superheavy Elements Factory – SHEF – in JINR) should start operating to satisfy these challenges soon (see [11] in this Proceeding for details).

Another way is to use ^{48}Ca-induced reactions and to study less probable reaction channels with evaporations of 2 and 5 neutrons from compound nuclei. Up to now ^{294}Ts (N=177) and ^{294}Og (N=176) are the two heaviest nuclei from the valley of SHE around N=184. Thus, performing the ^{248}Cm(^{48}Ca,2*n*)^{294}Lv and ^{249}Bk(^{48}Ca,2*n*)^{295}Ts reactions could lead to ^{294}Lv (N=178) and ^{295}Ts (N=178). Reactions with the heaviest available today target material, ^{251}Cf, could produce ^{295}Og, ^{296}Og, and ^{297}Og (N=177, 178, and 179). Their decay descendants will pass through nuclides with already known properties.

Reactions with lighter target materials (^{239,240}Pu, ^{241}Am) and ^{48}Ca beam could explore the left-hand edge of the “Island of stability” and observe decays of the lightest isotopes of $^{282\text{-}285}$Fl and $^{282\text{-}286}$Mc nuclei in corresponding 2-5*n*-evaporation reaction channels. Two new ^{284}Fl and ^{285}Fl isotopes have been already synthesized and studied in the reactions ^{239}Pu(^{48}Ca, 3*n*)^{284}Fl and ^{240}Pu(^{48}Ca, 4-3*n*)^{284,285}Fl [12].

In this work, we present the results of the experiment aimed at the synthesis of new Og isotopes in the $^{249\text{-}251}$Cf + ^{48}Ca fusion-evaporation reactions [13].

2. Experiment

The first identification of an isotope of ^{294}Og (Z=118) element was attempted and successful at JINR Dubna in 2002 using the ^{249}Cf+^{48}Ca reaction [14]. The ^{48}Ca beam energy was selected above the Coulomb barrier to create the ^{297}Og compound nucleus with an excitation energy E^{*} of about 29 MeV. With an accumulated beam dose of 2.5×10^{19} particles of ^{48}Ca at 245 MeV, a single decay chain of recoil tagged and correlated high-energy α-decays and spontaneous fission (recoil-α-α-SF) was detected. The estimated cross section for the 3n-reaction channel based on one observed event was 0.3 pb.

The second experiment with a ^{249}Cf target and ^{48}Ca beam was performed in 2005 at a higher beam energy of 251 MeV corresponding to the compound nucleus excitation energy range between 32 MeV and 37 MeV. Two additional events consistent with the first decay chain were detected, and the properties of all three decay chains attributed to ^{294}Og decay were presented in Ref. [14]. The half-life of ^{294}Og based on three α decays at the average energy of 11.65 ± 0.06 MeV was determined to be 0.89 ms. Two decay chains consisted of recoil-α-α-SF events and one longer decay chain terminated with SF after three consecutive α-decays. These observations are consistent with independently studied decay properties of the granddaughter isotope of ^{294}Og, ^{286}Fl, with similar decay probabilities through α-emission and spontaneous fission. The cross section at the beam energies used to observe these two new ^{294}Og events was estimated to be 0.5 pb for the excitation energy range E^* = 32.1–36.6 MeV [14].

One more event of ^{294}Og formation was observed in the experiment on Z=117 element synthesis as a result of the buildup of ^{249}Cf in the ^{249}Bk target material due to its β-activity [15]. The cross-section estimate for this single event of 0.3 pb for the excitation energy range of 26.6–37.5 MeV for ^{297}Og was also in good agreement with earlier deduced cross sections. The four-event average of ^{294}Og decays yielded $T_{1/2}$ of 0.69 ms and $E\alpha$ = 11.66 ± 0.06 MeV [15]. A summary of decay properties as they were experimentally known prior to mixed $^{249\text{-}251}$Cf target campaign is shown in Fig. 1a.

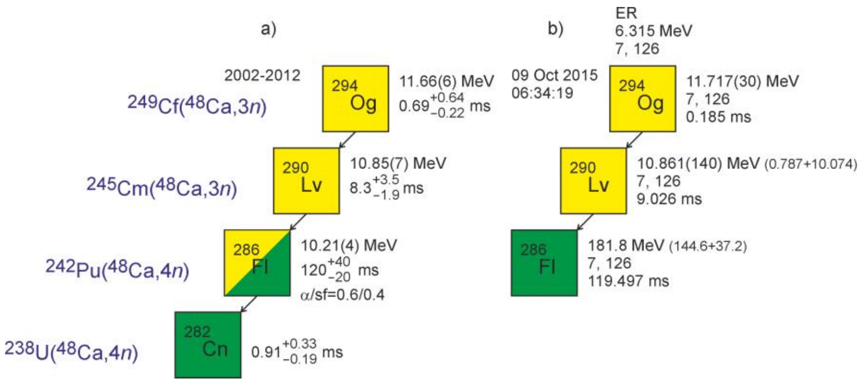

Fig. 1. a). Average decay properties ($T_{1/2}$ and E_α) of ^{294}Og-^{282}Cn determined in the reactions ^{48}Ca + ^{249}Cf, ^{245}Cm, ^{242}Pu, ^{238}U [1]. b). Properties of ^{294}Og-^{286}Fl decay measured in this work. The right rows provide energies, time intervals between events and their DSSD strip numbers for α-decay and SF. Energies of summed signals are given in parentheses.

The new series of the experiments was undertaken at the DGFRS during October, 2015 – April, 2016. The target of mixed Cf isotopes (50.7% of ^{249}Cf, 12.9% of ^{250}Cf, 36.4% of ^{251}Cf) was provided by Oak Ridge National Laboratory (ORNL, TN). Twelve identical sectors were delivered to FLNR in February 2015 and were mounted on a disk that was rotated at 1700 rpm so that the target was perpendicular to the direction of the incoming beam. In the course of the bombardment with the ^{48}Ca beam, the target layers were systematically monitored by counting α-particles from the decay of the target isotopes [13]. The lab-frame beam energies in the middle of the target layers, excitation energy ranges and beam doses for the experiments studied are summarized in Table I.

Table I. The target material, lab-frame beam energies in the middle of the target, resulting excitation-energy intervals, total beam doses, and numbers of observed decay chains assigned to the parent nuclei ^{294}Og (3*n*) are listed.

Target nucleus	E_{lab} (MeV)	E_{exc} (MeV)	Beam dose $\times 10^{19}$	Number of chains 2*n*/3*n*/4*n*/5*n*	Ref.
^{249}Cf	245	26.6–31.7	2.5	- / 1 / - / -	[14]
	251	32.1–36.6	1.6	- / 2 / - / -	[14]
^{249}Cf*	252	26.6–37.5	1.6	- / 1 / - / -	[15]
^{249}Cf	252	33.0–37.4	1.6	- / 1 / - / -	[13]
	258	37.8–42.4	1.1	- / - / - / -	[13]
^{251}Cf	252	34.2–38.6	1.6	- / - / - / -	[13]
	258	39.0–43.6	1.1	- / - / - / -	[13]

* ^{249}Cf as buildup result of ^{249}Bk β-decay ($T_{1/2}$ = 327 d).

The array of Silicon detectors at the DGFRS final focus has been modified to increase the position resolution of recorded signals and subsequently reduce the probability of observing sequences of random events that mimic decay chains of implanted nuclei. The new detection system includes a 0.3-mm thick Double-sided Silicon Strip Detector (DSSD) manufactured by Micron Semiconductor Ltd. This large DSSD has 1-mm wide strips, 48 at the front side and 128 at the back side, creating over 6000 1-mm^2 pixels in one Silicon wafer. Such high pixilation helps to achieve superior position resolution for recoil-correlated decay sequences reducing potential random events. This new Si-detector array was designed, assembled, commissioned off-line and provided by ORNL. The signals from all detectors were processed using MESYTEC linear preamplifiers. Further, these analog signals were split into two independent measurement branches by special spectroscopic splitter-amplifier PA32-64 designed by the DGFRS group. Thus, all detectors' signals were processed simultaneously by analog electronics similar to those used in previous DGFRS experiments [1, 9, 12, 14, 15], and by digital electronics system based on XIA Pixie-16 modules provided by ORNL. This new DSSD assemblage and two independent registering systems were successfully applied recently in ^{239}Pu +

^{48}Ca and ^{240}Pu + ^{48}Ca experiments [12]. The FWHM energy resolution of the implantation detector was 34 to 78 keV depending on the strip, while the summed signals recorded by the side and implantation detectors had an energy resolution of 147 to 263 keV. Other experimental conditions, including the method of calibration of the detectors, were the same as in previous DGFRS experiments (see [1] and references therein).

3. Results

Present experiment with mixed $^{249\text{-}251}$Cf target was carried out at two ^{48}Ca-beam energies, see Table I. At the beam energy E = 252 MeV with accumulated beam dose of 1.6×10^{19} particles just one correlated decay chain (Fig. 1b) was observed which we assign to ^{294}Og, the product of 3*n*-evaporation channel of the ^{249}Cf(^{48}Ca, 3*n*)^{294}Og reaction which was studied at the DGFRS earlier. Its decay properties reproduce in full those observed in [1, 14, 15]: the new decay chain consists of implanted recoil nuclei, two following α–particles and terminates by SF of ^{286}Fl. The cross section of the ^{249}Cf(^{48}Ca,3*n*)^{294}Og reaction for 252-MeV projectiles was measured (Fig. 2) to be about 0.9 pb. For the ^{251}Cf(^{48}Ca,3*n*)^{296}Og reaction the upper cross section limit is set at the level of 3.4 pb.

At 258 MeV beam energy the bombardment was performed with the aim to produce ^{295}Og or ^{296}Og isotopes, the products of the ^{251}Cf(^{48}Ca,*xn*)$^{299\text{-}x}$Og reaction with evaporation of 4 and 3 neutrons. The beam dose of 1.1×10^{19} particles was accumulated during 56 days, no decay chains were observed at this energy which could be attributed to SHN. The upper bounds for the cross section are 4.1 pb for ^{294}Og and 5.7 pb for ^{296}Og [13].

Finally, this experiment was stopped due to significant pollution of the target material caused by melted glue from sector frames which covered all the target sectors and prevented ERs escaping from the target (the target surface was monitored during the experiment by registering the α–particle count from the target). The target was sent back to ORNL for the regenerating. After recovering it looks optimistic to use mixed Cf target and ^{48}Ca beam for the producing the heaviest ^{295}Og and ^{296}Og isotopes.

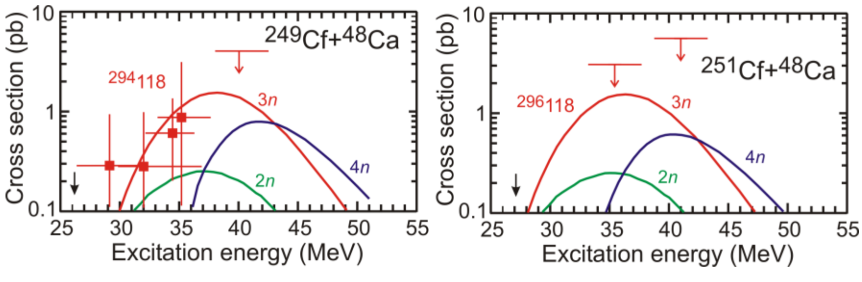

Fig. 2. The calculated excitation functions [16] of the ^{249}Cf(^{48}Ca,xn)$^{294\text{-}x}$Og and ^{251}Cf(^{48}Ca,xn)$^{299\text{-}x}$Og reactions and the experimental data [1, 13-15].

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