Study of the $^{249-251}$Cf + $^{48}$Ca reactions: recent results and outlook

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Abstract. Experiment aiming at the synthesis of heavy isotopes of Z=118 (Og) using beam of $^{48}$Ca and a target of $^{249-251}$Cf was undertaken in October 2015 – April 2016 employing the Dubna Gas-Filled Recoil Separator (FLNR JINR). The target of mixed isotopes of $^{249-251}$Cf (50.7% of $^{249}$Cf, 12.9% of $^{250}$Cf, and 36.4% of $^{251}$Cf) was irradiated by $^{48}$Ca ions at two beam energies of 252 and 258 MeV with the corresponding accumulated beam doses of $1.6 \times 10^{19}$ and $1.1 \times 10^{19}$. A single event observed at lower beam energy was assigned to the isotope $^{294}$Og, the product of the reaction $^{249}$Cf($^{48}$Ca, 3n); its decay pattern and the observed radioactive properties of the nuclides in the decay chain reproduce in full those observed for $^{294}$Og in our earlier experiments of 2002-2005 and 2012. At higher beam energy we observed no decay chains that could be attributed to the isotopes of Og. The possibility of renewal of this experiment in the future is discussed.

1. Introduction

More than 50 new isotopes of the nuclei with Z = 104-118 from the predicted “Island of stability” of superheavy elements (SHE) were synthesized for the first time at the Flerov Laboratory of Nuclear Reactions (JINR, Dubna) using Dubna Gas-Filled Recoil Separator (DGFRS) and heavy ions cyclotron U-400 during last 15 years (Fig. 1). The complete-fusion reactions of $^{238}$U, $^{237}$Np, $^{242},^{244}$Pu, $^{243}$Am, $^{245},^{246}$Cm, $^{248}$Bk and $^{249}$Cf targets with $^{48}$Ca ions were studied and cross sections of these reactions were measured [1]. Recently, these results were approved also by the other researches performed by IVO [2], SHIP [3], BGS [4] and TASCA [5-7] experimental setups. Decay properties of these nuclei that belong to the domain of superheavy nuclei, point to a considerable stabilizing effect when approaching the predicted neutron closure shell at N=184.

Few attempts have been also undertaken to expand the region of SHN by synthesis of elements 119 and 120 with target nuclei ranging from $^{238}$U to $^{249}$Cf and projectiles heavier than $^{48}$Ca. Five reactions $^{64}$Ni + $^{238}$U (SHIP [8]), $^{58}$Fe + $^{248}$Pu (DGFRS [9]), $^{54}$Cr + $^{246}$Cm (SHIP [10]), $^{50}$Ti + $^{246}$Bk (TASCA
[11]) and \(^{50}\)Ti + \(^{249}\)Cf (TASCA [12]) were employed, however, no decay chains of SHE were observed in these experiments. The upper cross section limits were set at 0.07 – 1.1 pb range depending on the reaction.

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\begin{array}{c}
\text{Chart of nuclides} \\
\text{Proton number} \\
\text{Neutron number} \\
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![Chart of nuclides](image)

**Fig. 1.** The top of the nuclear landscape with the heaviest identified nuclei and their measured half-lives and decay modes that were obtained in \(^{48}\)Ca-induced reactions. White squares show the isotopes \(^{289}\)Lv, \(^{293}\)Og, \(^{295}\)Og and \(^{296}\)Og which can be produced in \(^{249-251}\)Cf+Ca reactions.

Recently we continued exploring the island of stability of the SHN employing the DGFRS in searching for the new isotopes at the edge of the new SHE region. In irradiation of \(^{249-251}\)Cf targets with \(^{48}\)Ca beam three new isotopes of the heaviest 118 element can be produced (Fig. 1). New nuclide \(^{288}\)Lv can be observed as daughter of \(^{290}\)118. Two new isotopes \(^{284}\)Fl and \(^{285}\)Fl have been already synthesized and studied in the reactions \(^{249}\)Pu(\(^{48}\)Ca, 4-3n)\(^{283,284}\)Fl and \(^{249}\)Pu(\(^{48}\)Ca, 4-3n)\(^{284,285}\)Fl [13].

In this work, we present the preliminary results of the new campaign aimed at the synthesis of new Og isotopes in the \(^{249-251}\)Cf + \(^{48}\)Ca fusion-evaporation reactions.

### 2. Experiment

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 \(\alpha\)-particles from the decay of the target isotopes. 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.

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-mm² 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 [17]. Further, these analog signals were split into two independent measurement branches by special spectroscopic splitter-amplifier PA32-64 [18] designed by DGFRS group. Thus, all detectors’ signals were processed simultaneously by analog electronics similar to those used in previous DGFRS experiments [19], and by digital electronics system based on XIA Pixie-16 modules provided by ORNL [20]. This new DSSD assemblage and two independent registering systems were successfully applied recently in 239Pu + 48Ca and 240Pu + 48Ca experiments, see [13].

Table I. The 249Cf target thickness, 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 249Og (3n) are listed.

| Reaction     | Target thickness (mg/cm²) | E_\text{lab} (MeV) | E_\text{exc} (MeV) | Beam dose x10^19 | Number of chains 2n / 3n / 4n / 5n | Ref. |
|--------------|--------------------------|---------------------|---------------------|------------------|-----------------------------------|-----|
| 249Cf + 48Ca | 0.23                     | 245                 | 26.6 – 31.7         | 2.5              | / 1 / - / -                      | [14]|
| 249Cf + 48Ca | 0.34                     | 251                 | 32.1 – 36.6         | 1.6              | / 1 / - / -                      | [15]|
| 249Cf + 48Ca | 0.30                     | 252                 | 26.6 – 37.7         | 1.6              | / 1 / - / -                      | [16]|
| 251Cf + 48Ca | 0.35                     | 252                 | 33.0 – 37.4         | 1.6              | / 1 / - / -                      | This work|
| 251Cf + 48Ca | 0.35                     | 258                 | 37.8 – 42.4         | 1.1              | / 1 / - / -                      | This work|

* 249Cf as buildup result of 249Bk β-decay (T_1/2 = 320 d).

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

One of the heaviest nuclei from the “Island of Stability”, the isotope 294Og, was produced for the first time in the 249Cf + 48Ca reaction in 2002 [14]. Three years later in the same reaction we observed two similar decay chains more [15]. Additionally, the fourth event of 294Og formation was observed in the experiment on Z=117 isotopes synthesis as a result of the buildup of 249Cf in the 249Bk target material due to its β-activity [16].

Present experiment with mixed 249-251Cf target was carried out from October 1, 2015 till April 6, 2016 at two 48Ca-beam energies. See Table I. At the beam energy E = 252 MeV with accumulated beam dose of 1.6 x 10^19 particles just one correlated decay chain was observed which we assign to 294Og, the product of 3n-evaporation channel of the 249Cf(48Ca, 3n)294Og reaction (Fig. 2). Its decay properties reproduce in full those...
observed in [14-16]. The cross section of the $^{249}$Cf($^{48}$Ca,3$n$)$^{294}$Og reaction for 252-MeV projectiles was measured to be about 0.9 pb (Fig. 3).

At 258 MeV beam energy the bombardment was started on February 10, 2016 with the aim to produce $^{295}$Og or $^{296}$Og isotopes, the products of the $^{251}$Cf($^{48}$Ca,$n$)$^{294}$Og reaction with evaporation of 4 and 3 neutrons. The beam dose of $1.1 \times 10^{19}$ particles was accumulated during 56 days, no decay chains were observed at this energy which could be attributed to SN.

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 of the $\alpha$-particle count from the target). The target was sent back to ORNL for the regenerating. We are looking forward for continuation of this experiment with $^{249,251}$Cf target in 2017-2018.

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