EXPERIMENTS ON THE SYNTHESIS OF ELEMENT 115 IN THE REACTION
$^{243}\text{Am (}^{48}\text{Ca, }x\text{n)}$ $^{291-115}$


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Our previous experiments were designed to synthesize even-Z superheavy elements (114-118) in $^{48}\text{Ca}$-induced reactions with actinide targets $^{242,244}\text{Pu}$, $^{245,248}\text{Cm}$ and $^{249}\text{Cf}$ [1,2]. The observed fusion-evaporation reaction products underwent two or three consecutive $\alpha$ decays and were terminated by spontaneous fission (SF). For the neighboring odd-Z elements, especially their odd-odd isotopes, the probability of $\alpha$ decay with respect to SF should increase due to the large hindrance against SF. For such odd-Z nuclei one might expect longer consecutive $\alpha$-decay chains terminated by the SF of lighter descendant nuclides. The increased stability of nuclei caused by the predicted spherical neutron shell at $N=184$ should gradually become weaker for descendant nuclei. However, the stability of the nuclei at the end of these decay chains should increase again due to the influence of the deformed shell at $N=162$.

For these investigations, we chose the $^{243}\text{Am+}^{48}\text{Ca}$ reaction, leading to isotopes of element 115. The experiments were performed between July 14 and August 10, 2003 [3]. During the experiment, equal beam doses of $4.3 \times 10^{18} \text{ }^{48}\text{Ca}$ projectiles were delivered to the target at bombarding energies of 248 and 253 MeV. The excitation energies of compound nuclei were between 38.0-42.3 and 42.4-46.5 MeV, respectively. The $^{243}\text{Am}$ (99.9%) target material was deposited onto 1.5-μm Ti foils to a $^{243}\text{Am}$ thickness of 0.36 mg cm$^{-2}$. The evaporation residues (ERs) were separated in flight by the Dubna Gas-Filled Recoil Separator (DGFRS). The transmission efficiency of the separator for $Z=115$ nuclei was estimated to be 35%. To greatly reduce the background, we switched off the beam after a recoil signal was detected

![Fig. 1 Time sequences in the decay chains observed at two $^{48}\text{Ca}$ energies. Measured energies, time intervals and vertical positions of the observed decay events are shown. 1) Energies of events detected by both the focal-plane and side detectors. 2) Energies of events detected by side detectors only.](image-url)
with an implantation energy expected for $Z=115$ ERs, followed by an $\alpha$-like signal with an energy of 9.6-11.0 MeV in the same strip, within a position window of 1.4-1.9 mm and time interval of up to 8 s. The total beam-off interval could last up to 2.7 hours.

The three similar decay chains observed at 248 MeV are shown in Fig. 1a. At 253 MeV, a different decay chain was registered (see Fig. 1b). The radioactive properties of the nuclei in this decay chain differ from those of the nuclei observed at the lower bombarding energy. In addition, its production was observed when the beam energy was increased by 5 MeV. It is most reasonable that the two different decay chains originated from neighboring parent isotopes of element 115. Indeed, at the excitation energy $E^*=40$ MeV, close to the expected maximum for the $3n$-evaporation channel, we observed longer decay chains assigned to the odd-odd isotope $^{288}115$. Increasing the beam energy by 5 MeV results in reducing the $^{288}115$-isotope yield and increasing the yield of the $4n$-evaporation channel leading to the odd-even isotope $^{287}115$. The corresponding cross sections for the $3n$ and $4n$ channels are $\sigma_{3n}=2.7\pm0.8$ pb (248 MeV) and $\sigma_{4n}=0.9\pm0.1$ pb (253 MeV).

In a single decay chain originating from $^{287}115$, we propose that we missed the $\alpha$ decay of $^{271}Bh$. This assumption follows from the $\alpha$ decay properties of nuclei located around $N=162$ as predicted by theory [6]. The expected $T_\alpha$ value for $^{271}Bh$ should be ~10 s ($Q_\alpha=9.07$ MeV [6], $T_\alpha\approx5$ s for an allowed transition), which is much shorter than the interval between the last observed $\alpha$ particle and the terminating SF-event, but is much longer than the intervals between the observed correlated $\alpha$ particles. In the correlated decay chains shown in Fig. 1, 19 $\alpha$ particles were

In an independent experiment, the atomic numbers of all of the nuclei from the $^{288}115$ decay chain were determined by chemical identification of the final SF nucleus [4]. The spontaneous fission activity was observed in the group 5 chemical fraction consistent with the decaying nuclide being $^{268}Db$ ($Z=105$).

In the decay chains shown in Fig. 1a, we assigned SF events to $^{268}Db$. It is also possible that this isotope undergoes electron capture (EC); $\alpha$ decay of $^{268}Db$ is excluded by the results of the chemical experiment [4]. The electron capture of $^{268}Db$ leads to the even-even isotope $^{268}Rf$, for which rapid spontaneous fission can be expected ($T_{SF}=1.4 \text{ s} [5]$). The likelihood that EC decay occurs earlier in the observed decay chains is small because of the short $T_\alpha$ for the observed $\alpha$ decays of elements 107 (Bh) - 115.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Decay mode</th>
<th>Half-life$^a$</th>
<th>$E_\alpha$ (MeV)</th>
<th>$Q_\alpha$ (MeV)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{288}115$</td>
<td>$\alpha$</td>
<td>$87_{-30}^{+30}$ ms (60 ms)</td>
<td>10.46±0.06</td>
<td>10.61±0.06 (10.95)</td>
</tr>
<tr>
<td>$^{284}113$</td>
<td>$\alpha$</td>
<td>$0.48_{-0.17}^{+0.58}$ s (0.3 s)</td>
<td>10.00±0.06</td>
<td>10.15±0.06 (10.68)</td>
</tr>
<tr>
<td>$^{280}Rg$</td>
<td>$\alpha$</td>
<td>$3.6_{-1.3}^{+4.3}$ s (0.4 s)</td>
<td>9.75±0.06</td>
<td>9.87±0.06 (10.77)</td>
</tr>
<tr>
<td>$^{276}Mt$</td>
<td>$\alpha$</td>
<td>$0.72_{-0.25}^{+0.87}$ s (0.1 s)</td>
<td>9.71±0.06</td>
<td>9.85±0.06 (10.99)</td>
</tr>
<tr>
<td>$^{272}Bh$</td>
<td>$\alpha$</td>
<td>$9.8_{-3.5}^{+11.7}$ s (3 s)</td>
<td>9.02±0.06</td>
<td>9.15±0.06 (9.08)</td>
</tr>
<tr>
<td>$^{268}Db$</td>
<td>SF/EC</td>
<td>16$^{+19}_{-6}$ h (6 h)</td>
<td>(7.80)</td>
<td></td>
</tr>
</tbody>
</table>
registered using a detector with 87% efficiency, so the loss of one α particle seems rather probable. The experimental decay scheme for 287\textsuperscript{115} is also supported by the agreement of the observed decay properties of the other nuclides in the decay chain with the expectations of theory. This means that the SF occurs directly in the decay of 267\textsubscript{Db} since the calculated α-decay energies and EC-decay energies for this isotope are low ($Q_{\alpha}=7.41$ MeV [6], $Q_{EC}=0.79$ MeV [7]) and their expected partial half-lives significantly exceed the observed time interval of 106 min.

The decay properties of the observed nuclei are presented in Table I. For the measured α decay energies of the newly-produced isotopes, one can estimate the half-lives for allowed transitions using the Viola and Seaborg formula and then compare them with experimental values. The ratio of experimental $T_{exp}$ and calculated $T_{calc}$ half-lives define the hindrance factors caused by odd numbers of protons and/or neutrons in the nuclei. The measured $T_{exp}$ values closely reproduce the calculated ones for the first two nuclei of these chains; thus the element 115 and element 113 isotopes have rather low α-decay hindrance factors. For the isotopes of Rg, Mt and Bh, the difference between the measured and calculated $T_{\alpha}$ values results in hindrance factors of 3-10. These match the hindrance factors that can be extracted for the deformed odd-odd nuclei 272\textsubscript{Rg} and descendants [8]. One can suppose that in this region of nuclei, a noticeable transition from spheroidal to deformed shapes occurs at $Z=109-111$, resulting in an increased probability of α transitions going through excited states. Another sign of such a shape transition might be the significant increase in the difference of α-decay energies of the neighboring isotopes observed as the decay chains reach $Z=111$. In the decay chains of even-Z nuclei, we observed a similar variation in α-decay energies [1,2]. This assumption is in agreement with calculations [6].

The deformation parameter $\beta_2$ was calculated to be 0.072 and 0.138 for 288\textsubscript{115} and 284\textsubscript{113}, respectively. As the decay chain recedes from the shell closure at $Z=114$, the deformation parameter $\beta_2$ increases to 0.200, 0.211 and 0.247 for 280\textsubscript{111}, 276\textsubscript{Mt} and 272\textsubscript{Bh}, respectively.

The α-decay energies attributed to the isotopes of Mt and Bh coincide well with theoretical values [6]. For the isotopes 279,280\textsubscript{111} and 283,284\textsubscript{113} the difference between theoretical and experimental $Q_{\alpha}$ values amount to 0.6-0.9 MeV. While the predicted $Q_{\alpha}$ values for the heaviest nuclei are systematically larger than the experimental data as a whole, the trends of the data are in good agreement, considering that these theoretical predictions of the MM model are matched over a broad unexplored nuclear domain by the measured $Q_{\alpha}$ values for 23 nuclides with $Z=106-118$ and $N=165-177$ [1-3].

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REFERENCES