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First experiment at the Super Heavy Element Factory: High cross section of ^{288}Mc in the ^{243}Am + ^{48}Ca reaction and identification of the new isotope ^{264}Lr

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We present results of the first experiment aimed at the synthesis of Mc isotopes in the ^{243}Am + ^{48}Ca reaction performed at the new gas-filled separator DGFRS-2 online to the new cyclotron DC280 at the Super Heavy Element Factory at JINR. Fifty-five new decay chains of ^{288}Mc and six chains assigned to ^{289}Mc were detected. The α decay of ^{268}Db with an energy of 7.6–8.0 MeV, half-life of 16^{+6}_{-4} h, and a branch of $55^{+20}_{-15}\%$ was registered for the first time, and a new spontaneously fissioning isotope ^{264}Lr with a half-life of $4.9^{+2.1}_{-1.3}$ h was identified. The cross section for the ^{243}Am(^{48}Ca, $3n$)^{288}Mc reaction was measured to be $17.1^{+6.3}_{-4.7}$ pb, which is the largest value for the known superheavy nuclei at the island of stability.

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The isotopes of the element 115, ^{288}Mc and ^{287}Mc, were first synthesized in 2003 in the ^{243}Am + ^{48}Ca reaction at the DGFRS separator [1]. In 2010–2012, another series of experiments was carried out at a ^{48}Ca-beam energy range of 240–254 MeV [2]. Following these experiments, we assigned four decay chains, consisting of two α decays and spontaneous fission (SF) and occurring within about a minute, to ^{289}Mc parent activity. Other long chains (five consecutive α decays and SF) were assigned to ^{288}Mc (31 chains) and to ^{287}Mc (2 chains). In addition, ^{289}Mc and ^{290}Mc isotopes were observed as descendants of α decay of ^{293,294}Ts isotopes, products of the ^{249}Bk + ^{48}Ca reaction, in two experiments performed in 2009–2010 and 2012 (20 decay chains in total [3]). It is known that the complex α-particle spectrum of odd-Z and/or odd-N nuclei makes their identification more difficult. However, based on the combined analysis of the radioactive properties, observations at different energies of ^{48}Ca beams, as well as in reactions with different targets (^{243}Am and ^{249}Bk), we attributed decay chains observed in these reactions to the ^{287}Mc, ^{288}Mc, and ^{289}Mc parent activities.

In 2013 and 2015, results of experiments, performed at the separators TASCA (GSI) [4] and BGS (LBNL) [5], were presented. The products of the ^{243}Am + ^{48}Ca reaction were studied by methods of α-, x-ray, and γ-coincidence spectroscopy. Twenty-two decay chains were assigned to ^{288}Mc and one to ^{287}Mc in [4]. In [6] it was discussed that seven short decay chains, along with ^{289}Mc, could also be due to different branches of ^{288}Mc decay. In [5], all the 46 synthesized chains, including three short ones, were assigned to ^{288}Mc. In these works, owing to the observation of α-γ coincidences, α-decay energies of several chain members were measured and the level schemes of ^{276}Mt and ^{272}Bh were proposed. Short and long chains (two chains of ^{293}Ts and two of ^{294}Ts) were also observed in the ^{249}Bk + ^{48}Ca reaction in [7]. In both short chains of ^{293}Ts, as in 2 of 16 in [3], after α decay of ^{281}Rg with $E_\alpha = 9.3$ MeV, spontaneous fission with a half-life of about 5 ms was observed.

Finally, in 2018, results of experiments aimed at measuring the mass number of the ^{243}Am + ^{48}Ca reaction products at the FIONA setup were published [8]. The masses of the first nuclei in the two chains were found to be about 288 and 284 (after ^{288}Mc decay), which confirmed the initial assignment of the chains to the ^{288}Mc isotope.

In addition to physical experiments, an experiment was also performed to study the chemical properties of ^{288}Mc and/or its descendant nuclei [9]. Five decay chains were assigned to ^{288}Mc.

Despite the fact that the number of Mc isotope chains is about half of all the chains of superheavy nuclei observed in the ^{48}Ca-induced reactions with actinide targets, a number of

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TABLE I. The ^{243}Am target thickness, laboratory-frame energies of ^{48}Ca in the middle of the target layer, resulting excitation energy intervals (with use of mass tables [16,17]), total beam doses, the numbers of observed decay chains assigned to ^{288}Mc ($3n$) and ^{289}Mc ($2n$), and the cross sections of their production.

Target thickness (mg/cm^2)	E_{lab} (MeV)	E^* (MeV)	Beam dose $\times 10^{18}$	No. of chains $3n/2n$	σ_{3n} (pb)	σ_{2n} (pb)
0.36	243.9	35.5–37.8[a]	8.0	30/5	$9.8^{+2.6}_{-2.1}$	$1.6^{+1.2}_{-0.7}$
0.38	240.9	33.1–35.2[a]	2.2	16/1	$17.1^{+6.3}_{-4.7}$	$1.1^{+2.5}_{-0.9}$
0.38	239.1	31.5–33.6[a]	2.3	9/0	$9.9^{+5.1}_{-3.4}$	<2.1

[a]The masses by Myers and Swiatecki were used in our earlier papers. The excitation energies may differ by several MeV if later predictions are used; see, e.g., recent work [18] and references therein.

important questions require additional study. These include the following: The mass of the parent nucleus in short chains, the possible existence of different half-lives for ^{276}Mt, the probability of electron capture in heavy nuclei populated at the Mc decay chains, the cross section of the fusion-evaporation reaction channel with proton emission, and the probability of α decay of ^{268}Db.

Fortunately, the $3n$-evaporation cross section for the reaction with ^{243}Am is one of the largest among the reactions of actinide nuclei with ^{48}Ca, making this reaction perfectly suitable for testing equipment designed to study superheavy nuclei.

A new experimental complex, the Super Heavy Element Factory (SHE Factory) with a new cyclotron DC280, was put into operation at the end of 2019. The beam intensity of ^{48}Ca ions at DC280 can reach 10 pμA at consumption rate of enriched isotope of about 1.5 mg/h [10]. To study the products of fusion reactions with low cross sections, a new separator DGFRS-2 was installed and tested in commissioning experiments [11]. It differs from the previous separator DGFRS by higher transmission of synthesized nuclei and lower background at the focal plane.

Among the tasks of experiments performed during the November 2020 to February 2021 period (see Table I) were tests of the DGFRS-2 in conditions of continuous operation, measurement of the average charge state of Mc ions in rarefied hydrogen with comparison to the systematics of charges measured at DGFRS [12,13], measurement of the distribution of nuclei over the final focus detector surface and comparison with the results of transmission calculations [14,15], as well as the study of background conditions.

The separator consists of five magnets in a $Q_vD_hQ_hQ_vD$ configuration, where D refers to a dipole magnet and Q to a quadrupole magnet, and the subscripts h and v stand for horizontal and vertical focusing, respectively [11]. The separator was filled with hydrogen at a pressure of 1.15 mbar, which was constantly pumped through the separator in the direction from the detector chamber to the target block. The detector chamber was separated from the DGFRS-2 volume by a Mylar foil of 0.7 μm thick and filled with pentane at a pressure of 1.60 mbar. During presented experiments, the volumes of the separator filled with hydrogen and the beam line were separated by a rotating Ti window 0.62 mg/cm^2 thick. In subsequent experiments, we used a differential pumping system [11].

The targets consisting of the enriched isotope ^{243}Am (99.5% enrichment) were produced by layer-by-layer electrodeposition. Six target sectors were mounted on a disk with a diameter of 15 cm and rotated at 1500 rpm. The beam intensity was gradually increased to 1.2–1.3 pμA. The beam energy is measured with a time-of-flight system, which has a systematic uncertainty of 1 MeV.

The focal detector of 48 mm in vertical and 220 mm in horizontal directions consisted of two double-sided strip detectors (DSSD) covering 48 $\times$ 128 mm^2 with 1 mm wide strips (BB17 (DS)-300, Micron Semiconductor Ltd.) in such a way that the front detector shielded part of the rear detector. Each two of the 48 front horizontal strips of both detectors were connected. The back strips were paired together to form 110 strips of 2 mm width. The focal detector was surrounded by eight 60 $\times$ 120 mm^2 side detectors (W4-300), each with 8 strips, forming a box with a depth of 120 mm. All signals in detectors with amplitudes above the threshold $E_{th} = 0.55$–0.6 MeV were recorded independently by digital and analog data acquisition systems.

In front of the detectors, two multiwire proportional chambers (MWPC) are installed to register nuclei arriving from the separator [11]. Analog electronics were used for online registration of spatial, energy, and temporal correlations of evaporation residues (ER) and α particles, registered with full energy in the focal detector, with parameters expected for implantation in detectors and α decay of Mc or daughter nuclei and turning the beam off, in about 0.1 ms, to observe decays of descendant nuclei under low background conditions.

The energies and decay times of nuclei in the chains of ^{288}Mc and ^{289}Mc are included in the Supplemental Material [19].

Based on the results of [7], where α decay of ^{270}Db ($N = 165$) with a half-life of 1 h was registered, and the assumption of the similarity of the decay properties of isotopes with $N = 163$ and $N = 165$, after online registration of ten decay chains of ^{288}Mc - ^{272}Bh, we prolonged the beam-off interval up to 3–4 h. During these stops, we did not observe α particles with $E_\alpha = 7$–9 MeV in the same strips of the focal detector where ^{288}Mc decays were observed, which would be expected for ^{268}Db α decay.

We also searched for α decays of ^{268}Db, after which fission of ^{264}Lr with a relatively short period would be observed. We selected the ^{288}Mc chains in which α-like events with $E_\alpha = 7$–10 MeV were recorded between decays of ^{272}Bh and spontaneous fissions (50 chains out of 55). The energy distribution of all α-like events as a function of their detection time with respect to the fission registration time in chains (the fission time is taken as a reference point) is shown in Fig. 1(a). As can be seen, in the time interval from -10 to 0 h and $E_\alpha = 7.6$–8.0 MeV, an increased concentration of events preceding the fission is observed, which indicates their nonrandom origin. Figure 1(b) shows time distribution of events with $E_\alpha = 7.6$–8.0 MeV. Fitting the distribution with exponent and with a constant background [20] made it possible to

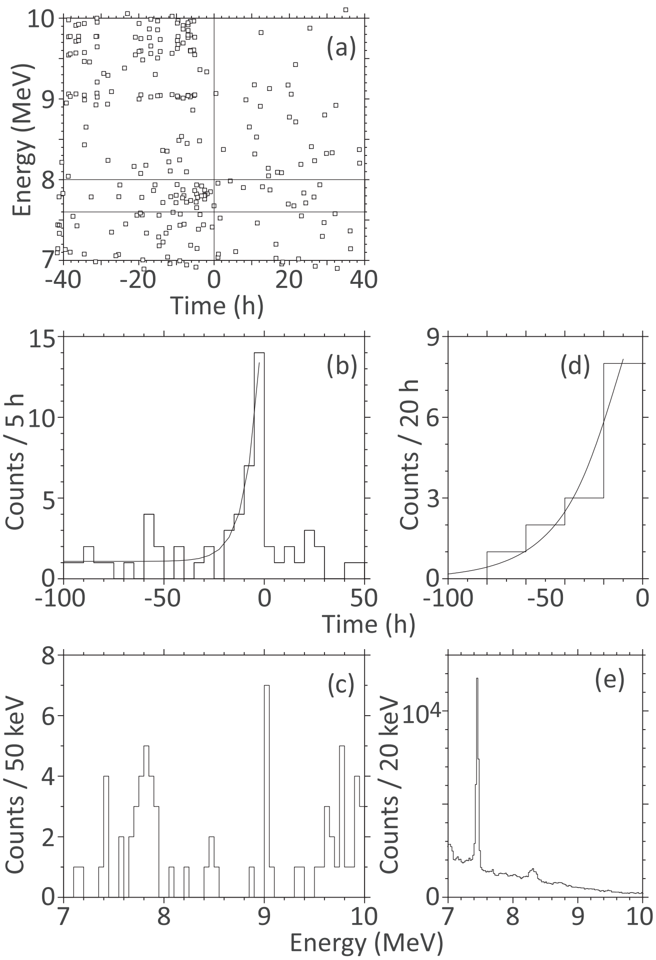

FIG. 1. Energy distribution of α-like events as a function of their detection time with respect to the SF registration time (a), time distribution of events with $E_\alpha = 7.6$–8.0 MeV (b), and energy distribution of events registered in the time interval of 10 h to SF (c). The most part of events with $E_\alpha \geqslant 9$ MeV originates from α decays of ^{272}Bh - ^{284}Nh [19]. Fig. 1(d) shows the decay curve of ^{268}Db; see text. Fig. 1(e) presents the spectrum of α-like events registered during all three runs.

determine the half-life of a spontaneously fissioning nucleus of $4.9^{+2.1}_{-1.3}$ h, which follows the α decay of ^{272}Bh and other nucleus with $E_\alpha = 7.6$–8.0 MeV. The energy distribution of events registered in the time interval of 10 h to SF is shown in Fig. 1(c). A peak in the 7.6–8.0 MeV range is visible. Figure 1(e) presents the spectrum of α-like events registered during all three runs, which shows the peaks of nuclei that remained in the detector after calibration experiments, e.g., ^{211}Po ($E_\alpha = 7.45$ MeV). The nonrandom nature of the 7.6–8.0 MeV peak is also evident from this spectrum. For example, the probability of observing 14 events in a peak at a background level of about 1 is less than 10^{-11}. The energy range of 7.6–8.0 MeV is in good agreement with what could be expected for ^{268}Db from the mass tables [16,21,22], as well as with the energy of 7.9 MeV attributed to ^{270}Db in [7]. Based on this, we assigned this α decay to ^{268}Db. In this case, spontaneous fission with a half-life of 4.9 h belongs to the new isotope ^{264}Lr.

During the 5-h interval before fission of ^{264}Lr, approximately one random α-like event is expected [Fig. 1(b)] which allows us to assume that this event will not significantly affect the half-life of ^{268}Db. From the time intervals between the α decays of ^{272}Bh and events with $E_\alpha = 7.6$–8.0 MeV, followed by spontaneous fission within 5 h, we calculated the half-life of ^{268}Db of 16^{+6}_{-4} h. The decay curve of ^{268}Db is shown in Fig. 1(d). The branch for α decay of $55^{+20}_{-15}\%$ was estimated from the number of decay chains of ^{288}Mc, the number of α-SF correlations shown in Fig. 1(b), and the detection efficiency of α particles with full energy. Since in all previous experiments the half-life of ^{268}Db was calculated from the time intervals between decays of ^{272}Bh and spontaneous fission which may originate from both ^{268}Db and ^{264}Lr, one can conclude that the half-life of ^{268}Db was also determined for the first time using its α-decay branch.

The energy spectra and time distributions of α particles of ^{288}Mc, ^{284}Nh, ^{280}Rg, ^{276}Mt, and ^{272}Bh observed in [1,2,4,5,8] and this work are shown in Fig. 1 in [19].

Among the decay times of ^{276}Mt reported in [2,4], three events have noticeably higher values (13.6, 16.9, and 8.95 s) than other events. This allowed us to assume the existence of two lifetimes for this isotope which might be caused by the predicted existence of isomeric states of nuclei in the transition region between the heaviest nuclei and nuclei located near the shells $Z = 108$ and $N = 162$ [2]. However, in the present work, the maximum decay time was 3.34 s. It cannot be ruled out that events with times higher than 5.2 s [2,4] were in fact due to the decay of ^{280}Rg or ^{272}Bh, in accord with Ref. [37] in [4]. The half-life of ^{276}Mt shown in Fig. 1 in [19] was calculated without taking these events into account.

Except for the above, the new data are in a good agreement with the previously known results. The half-lives measured in this work were 228^{+36}_{-28} ms, $0.77^{+0.13}_{-0.09}$ s, $3.2^{+0.6}_{-0.4}$ s, $0.51^{+0.08}_{-0.07}$ s, and $7.2^{+1.3}_{-0.9}$ s for isotopes ^{288}Mc, ^{284}Nh, ^{280}Rg, ^{276}Mt, and ^{272}Bh, respectively. These values are consistent with the data [23]. The energy spectra measured in this work are also in agreement with the spectra presented in [23] for the mentioned isotopes.

Similar data for nuclei in the short chains, which we attribute to parent nucleus ^{289}Mc, are shown in Fig. 2 [19]. These distributions also include events observed after the decay of ^{293}Ts [3,7]. It should be noted that the distributions of decay times for isotopes ^{289}Mc, ^{285}Nh, and ^{281}Rg satisfy the criterion for a single exponent suggested in [24]. The energy distributions of these isotopes differ from those shown in Fig. 1 in [19] for neighboring light isotopes. For example, the spectrum of ^{288}Mc has a peak with a maximum at $E_\alpha \approx$ 10.5 MeV, while the ^{289}Mc spectrum resembles a distribution consisting of two peaks at $E_\alpha \approx 10.35$ and 10.5 MeV, which were observed both in previous data and in this work. The spectra of daughter nuclei also differ, the majority of ^{284}Nh events have a rather narrow distribution, and the spectrum of ^{285}Nh is broader. The half-lives of isotopes are also systematically different; they are higher for heavier isotopes, which fully corresponds to the theoretical models predicting the region of enhanced stability for superheavy nuclei. This difference in $T_{1/2}$ is especially evident for the isotopes of Nh and Rg.

In six new short chains, we did not register α decay of ^{281}Rg followed by 4-ms fission of ^{277}Mt, which would more clearly determine the origin of this activity. As mentioned above, in experiments with a ^{249}Bk target, in 2 chains out of 16 in [3] and in both cases in [7], α decay of this isotope was registered. In experiments [2,5,6] with use of ^{243}Am target, 14 short chains were observed. Including the results of this work, the total number is 20. If we apply the results of [3] to estimate the α-decay branch for ^{281}Rg ($\approx$2/16 with taking into account the registration probability of α particle), the probability of nonobservation of α particle in 20 chains, following from the binomial distribution, is small ($\approx$6%), although the probability of registering two α decays in two chains is even less ($\approx$2%). In addition, it cannot be ruled out that in previous and the present experiments α decay of ^{281}Rg occurred, but was not registered. Taking into account the remaining uncertainties, we cannot completely exclude that short chains originate from another branch of the decay of ^{288}Mc, as is known, for example, for ^{261}Rf, although this is a fairly rare exception.

The decay chains of ^{288}Fl, products of the electron capture (EC/β^+) of ^{288}Mc or the $p2n$ channel of the ^{243}Am + ^{48}Ca reaction, were not evidently observed in this and previous experiments. The only candidate for these chains could be event T2 in [6], where an escaped α particle, registered solely by the front detector ($E_\alpha = 1.45$ MeV), in 64.5 ms after ER, was followed by SF in 366 ms. This may indicate that probability of EC/β^+ is about 0.7% or lower for ^{288}Mc. The level of the cross section of the $p2n$ channel is lower than that for the $3n$ channel by the same factor at ^{48}Ca energy close to maximum of the $3n$ channel. If we calculate the EC energy from the tables [17,22,25] and the EC partial half-life T_{EC} from the systematics shown in Fig. 9 in Ref. [23], the EC/β^+ branch for ^{288}Mc is expected to be $\leqslant$6% [17] or 4% [22,25]. Taking into account the uncertainty of such an assessment of T_{EC}, one can conclude that the results of the experiment qualitatively do not contradict these estimates.

The decay chains of ^{288}Mc where ^{284}Nh undergoes EC/β^+ should be registered as α decay of ^{288}Mc followed by SF of ^{284}Cn with lifetime of ^{284}Nh. Through 20 short decay chains observed in [2,5,6] and in this work, six cases resemble such chains. But applying the same method for estimation of EC/β^+ branch for ^{284}Nh, we get $\leqslant$10% [17], or 5–6% [22,25]. Again, we can say that the question of the EC/β^+ branch for ^{284}Nh requires further investigations.

The experiments were carried out at projectile energies close to the expected maximum of the $2n$- and $3n$-evaporation channels. For the $2n$ channel, the measured cross sections do not contradict the values measured in [2,6,23]; see Fig. 2. The maximum cross section of the $3n$ channel turned out to be twice the value measured at excitation energy of 34–38 MeV. In addition, the maximum appears to be shifted towards the lower excitation energy of 34 MeV. It should be noted that the uncertainties in the cross section are determined for a confidence level of 68%. Increasing the confidence level will obviously lead to overlapping measurement errors.

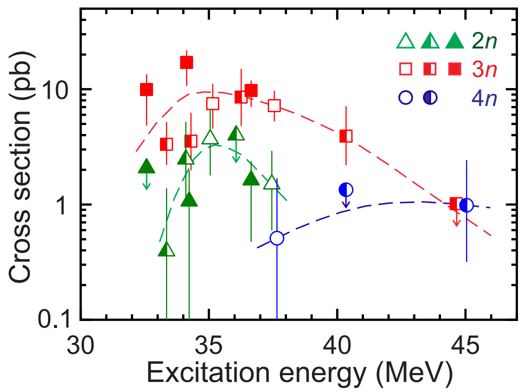

FIG. 2. Cross sections for the $2n$-, $3n$-, and $4n$-evaporation channels for the ^{243}Am + ^{48}Ca reaction. Vertical error bars correspond to total uncertainties. Symbols with arrows show upper cross-section limits. Data shown by open, half-closed, and closed symbols are from [6], [2], and this work, respectively. The dashed lines through the data are drawn to guide the eye.

In a series of test experiments [11], we studied the ^{206}Pb(^{48}Ca, $2n$) ^{252}No reaction at four ^{48}Ca energies to compare the position of the maximum of the excitation function with known data. The difference did not exceed 1 MeV in comparison with similar data from [26–28]. Somewhat lower values of the production cross section of ^{288}Mc at 32.0–36.4 and 31.4–36.2 MeV in [2] may be due to an overestimation of the target thicknesses, the beam doses, and/or the transmission of the separator. One can note also that the cross section for the reaction ^{242}Pu(^{48}Ca, $3n$) ^{287}Fl, measured at DGFRS-2 in recent experiments [29], also turned out to be higher than the values published in [23,30].

From comparison of experiments performed at $E^* \approx$ 36 MeV at DGFRS and DGFRS-2, as well as from calculations [14,15], it follows that the transmission of the new separator is about twice the transmission of DGFRS. According to calculations [14,15], the transmission of 60% was used for estimation of the cross sections.

In conclusion, a series of experiments on the synthesis of the ^{243}Am + ^{48}Ca reaction products at three projectile energies was carried out at the new separator DGFRS-2 of the SHE Factory to verify and extend the properties of Mc decay chains and to establish the capabilities for further research of superheavy nuclei. In total, 55 decays of ^{288}Mc and six short decay chains were recorded and assigned to ^{289}Mc. New data indicated some differences in decay properties of isotopes in long (^{288}Mc) and short (^{289}Mc) decay chains.

The α decay of ^{268}Db with an energy of 7.6–8.0 MeV, half-life of 16^{+6}_{-4} h, and an α branch of 55^{+20}_{-15}% was registered for the first time, and a new spontaneously fissioning isotope ^{264}Lr with a half-life of $4.9^{+2.1}_{-1.3}$ h was synthesized. The decay properties of all other isotopes are in good agreement with the data obtained during 2003–2018. The new data allowed us to determine the decay properties of isotopes with higher precision.

The measured cross section of $17.1^{+6.3}_{-4.7}$ pb for the ^{243}Am(^{48}Ca, 3n) ^{288}Mc reaction was approximately twice the value measured at DGFRS in [2] and represents the largest value for production of a known superheavy nucleus at the island of stability.

The transmission of the new separator DGFRS-2 was found to be about two times higher than the transmission of DGFRS. It demonstrates that the new SHE Factory is an excellent laboratory for continuing research on superheavy nuclei.

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