New isotope ^{286}Mc produced in the ^{243}Am + ^{48}Ca reaction

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In this paper, we present results of the second experiment on the synthesis of Mc isotopes in the ^{243}Am + ^{48}Ca reaction performed at the gas-filled separator DGFRS-2 of the SHE Factory at JINR. The new isotope ^{286}Mc was synthesized, and its half-life of 20^{+98}_{-9} ms and α-particle energy of 10.71 ± 0.02 MeV were determined. A ^{286}Mc α-decay chain was recorded down to the spontaneous fission of ^{266}Db. The spontaneous fission of ^{279}Rg was observed for the first time in one of four new decay chains of ^{287}Mc. The excitation function of the reaction was measured at three ^{48}Ca energies of 242, 250, and 259 MeV; the latter resulted in the first observation of the 5n-evaporation channel with a cross section of $0.5^{+1.3}_{-0.4}$ pb. The decay properties of 21 previously known odd-Z isotopes were improved. The potential for an electron-capture decay mode is discussed for ^{288}Mc and ^{284}Nh isotopes. The half-lives of spontaneously fissioning nuclei produced in the ^{48}Ca -induced reactions with actinide targets are compared with several theoretical predictions.

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I. INTRODUCTION

We present the results of experiments aimed at the study of the ^{243}Am + ^{48}Ca reaction at the gas-filled separator DGFRS-2 [1] online to the cyclotron DC280 at the SHE Factory (FLNR, JINR) [2]. The first series of these experiments was performed during the November 2020 to February 2021 period [3]. The purpose of the first series was to study the parameters of the new separator and the possibilities of its use for the synthesis of new elements heavier than Og ($Z = 118$). For this optimization, a reaction was chosen in which superheavy nuclei are formed with the largest cross section among other fusion reactions of actinide nuclei with ^{48}Ca. In addition to solving of technical issues, a more detailed study of the properties of nuclei in the decay chains of Mc isotopes as well as a measurement of the excitation function of the reaction were completed.

For the synthesis of new element 119, the reactions ^{243}Am + ^{54}Cr and ^{248}Cm + ^{51}V can be used to create $^{297}119^*$ and $^{299}119^*$ compound nuclei. The α-emission products of the 3n- and 4n-evaporation channels lead to new isotopes of $Z = 117$ Ts and to the following neutron-deficient isotopes ^{285,286}Mc and ^{287,288}Mc, respectively. Therefore, the decay properties of the latter are important for the identification of new superheavy elements and nuclei. However, only three decays of ^{287}Mc were observed in the ^{243}Am(^{48}Ca, 4n) reaction, which was studied at DGFRS (see [4] and references therein) and TASCA [5]. The isotopes ^{285,286}Mc have not been observed in earlier studies. In the ^{237}Np(^{48}Ca, 3n) reaction, only two chains of ^{282}Nh, a daughter activity of ^{286}Mc, were produced [6]. In one of these ^{282}Nh chains, an α-particle energy of ^{274}Mt was measured with poor precision and the detected energy in the second chain was smaller by 0.5–0.8 MeV than that expected from the α-decay energy Q_α systematic for the ground-to-ground state transition for this isotope. Also, in the second chain, the spontaneous fission (SF) of ^{266}Db was missing.

The synthesis of isotopes ^{286}Mc and ^{287}Mc requires experiments with a fairly high sensitivity. The isotope ^{287}Mc was observed in the ^{243}Am(^{48}Ca, 4n) reaction with a maximum cross section of about 1 pb at the excitation energy of the compound nucleus $E^* = 45$ MeV [4]. The production cross section of the ^{243}Am(^{48}Ca, 5n)^{286}Mc reaction could be expected at a noticeably lower level. It should be noted that during all the studies of fusion reactions of actinide nuclei with ^{48}Ca, the products of the channel with evaporation of five

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TABLE I. Lab-frame beam energies in the middle of the target layer, resulting excitation energy intervals (with use of mass tables [9,10]), total beam doses, the numbers of observed decay chains assigned to ^{289}Mc (2n), ^{288}Mc (3n), ^{287}Mc (4n), and ^{286}Mc (5n), and the cross sections of their production.

E_{lab} (MeV)	E^* (MeV)	Beam dose × 10^{18}	No. of chains $2n/3n/4n/5n$	σ_{2n} (pb)	σ_{3n} (pb)	σ_{4n} (pb)	σ_{5n} (pb)
242.2	34.0–36.3	9.2	4/52/2/0	$1.2^{+1.0}_{-0.6}$	$15^{+5.}_{-3.}$	$0.6^{+0.7}_{-0.4}$	
250.8	41.3–43.5	2.0	0/3/1/0		$4.1^{+4.2}_{-2.3}$	$1.4^{+3.2}_{-1.2}$	
259.1	48.2–50.4	5.0	0/0/1/1			$0.5^{+1.3}_{-0.4}$	$0.5^{+1.3}_{-0.4}$

neutrons were detected only in two chains—in the reactions with ^{244}Pu [7] and ^{242}Pu [8]. The cross sections of these reactions, determined with a large statistical error, were about 1 and 0.6 pb, respectively. However, it is obvious that in order to improve the models of nuclear fusion with the subsequent formation of neutron-evaporation products, the cross section of channels with the evaporation of five neutrons are of particular interest for estimating the probability of survival of nuclei in the process of deexcitation of the compound nucleus.

II. EXPERIMENT

During November 10 to December 04, 2021, and February 2022, we performed experiments aimed at observation of Mc isotopes in the ^{243}Am + ^{48}Ca reaction at the gas-filled separator DGFRS-2. The experiments were performed at the cyclotron DC280 of the new experimental complex SHE Factory. Unlike the first series of experiments on the synthesis of Mc isotopes [3], a differential pumping system was installed in front of DGFRS-2 instead of a rotating entrance window [1]. Most of the other experimental conditions, including the method of calibration of the detectors, were the same as in [3].

The target consisted of the enriched isotope ^{243}Am (99.5%) and was produced by electrodeposition and had an average Am layer thickness of 0.36 mg/cm^2. Six target sectors were mounted on a disk with a diameter of 15 cm and rotated with a frequency of 1500 or 1700 rpm. The maximum beam intensity was 1.2–1.3 $p\mu$A. The settings of magnetic optical elements of DGFRS-2 were the same as at the end of the first series of experiments [3]. The chamber of DGFRS-2 was filled with hydrogen at a pressure of 0.89 mbar with constant flow though the separator to the pumping system. The detector chamber was separated from the DGFRS-2 volume by a Mylar foil of 0.7 μm thickness and filled with pentane at a pressure of 1.6 mbar. In front of the detectors, two multiwire proportional chambers were installed to register nuclei arriving from the separator. The focal detector consisted of 48 1-mm horizontal strips and 110 2-mm vertical strips. It is assembled out of two 48 × 128-mm^2 double-sided strip detectors (DSSDs), model BB17 (DS)-300 by Micron Semiconductor Ltd., mounted in such a way that the front detector shields a part of the rear detector. 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 × 120-mm^2 side detectors (W4-300), each with eight strips, forming a box with a depth of 120 mm. All signals in detectors with amplitudes above a threshold of 0.55–0.6 MeV were recorded independently by digital and analog data acquisition systems. The analog system was used for online registration of spatial, energy, and temporal correlations of evaporation residues (ERs) and α particles, registered with full energy in the focal detector. For parameters expected for implantation signals in the detectors and α decay of Mc or daughter nuclei, the beam was turned off to observe decays of descendant nuclei under low background conditions. Details of the detector system are given in [1].

III. RESULTS AND DISCUSSION

Experimental conditions and some results are summarized in Table I. The energies and decay times of nuclei in the chains of ^{286}Mc, ^{287}Mc, ^{288}Mc, and ^{289}Mc are included in the Supplemental Material [11].

The energy spectra of α particles originating from ^{286}Mc, ^{287}Mc, ^{288}Mc, and ^{289}Mc observed in [4–6,12–16], as well as in our recent experiments [3] and this work are shown in Fig. 1. For α-particle spectra, events with an energy resolution of $\leqslant$40 keV [full width at half maximum (FWHM) <95 keV] were selected (α-particle energy of ^{283}Nh of 10.214(42) MeV from chain 1 in Table III of the Supplemental Material [11] is also shown in Fig. 1). The half-lives shown in the figures have been extracted from all known data.

At a maximum beam energy of ^{48}Ca (see Fig. 2 below), we registered the α decay of a new isotope ^{286}Mc with an energy of 10.71 ± 0.02 MeV and a half-life of 20^{+98}_{-9} s (see Table IV in the Supplemental Material [11]). The energies of the α particles of ^{282}Nh, ^{278}Rg, and ^{270}Bh coincide with those values that were measured in the ^{237}Np (^{48}Ca, 3n) ^{282}Nh reaction [6]. The total energy of the α particle of ^{274}Mt has not been observed, but the decay times of the isotopes from ^{282}Nh to ^{270}Bh do not contradict the half-lives measured earlier. The decay time of ^{266}Db turned out to be lower than the value observed in [6] (31.7 min), however, this may be due to the statistical spread of the decay times of one nucleus. Both decay times satisfy the criterion for a single exponential decay suggested in [17]. The half-life determined by the two decay times of ^{266}Db is 11^{+21}_{-4} min.

The cross section for the ^{243}Am (^{48}Ca, 5n) ^{286}Mc reaction was measured for the first time for the reactions of

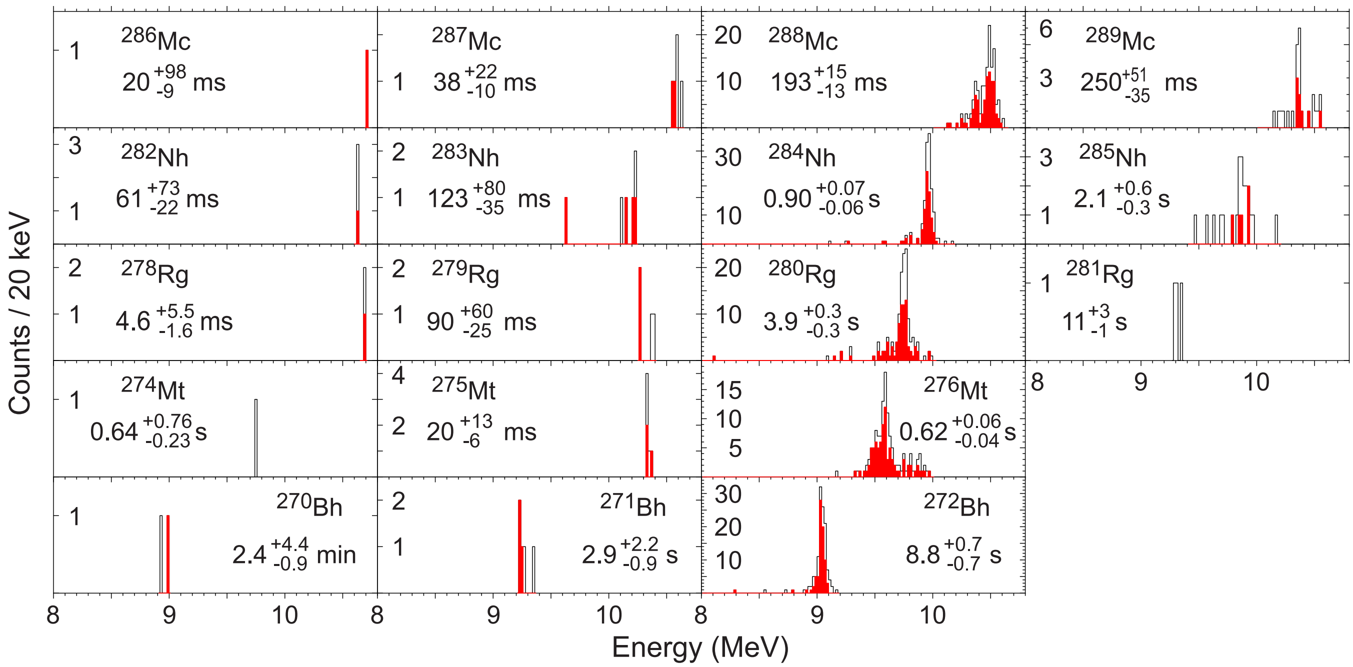

FIG. 1. Alpha-particle energy spectra for $^{286-289}$Mc and descendant nuclei. The events observed in [3] and in this work as well as a summary of previously known and new data are shown by full (red) and open histograms, respectively. The Y-axis scale values begin at zero.

^{48}Ca with odd-Z target nuclei and was $0.5^{+1.3}_{-0.4}$ pb at $E^* = 49$ MeV (Fig. 2). This value is close to those measured in the ^{244}Pu(^{48}Ca, $5n$)^{287}Fl ($1.1^{+2.6}_{-0.9}$ pb at $E^* = 53$ MeV) [7] and ^{242}Pu(^{48}Ca, $5n$)^{285}Fl ($0.6^{+0.9}_{-0.5}$ pb at $E^* = 50$ MeV) [8] reactions.

It is interesting to note that channels with evaporation from 2−3 to 5 neutrons from an excited nuclei are observed in all these reactions, and the cross section of the $5n$ channel is within two orders of magnitude of the maxima of the fusion-evaporation cross sections. This fact may indicate a relatively high survival probability of the superheavy compound nucleus

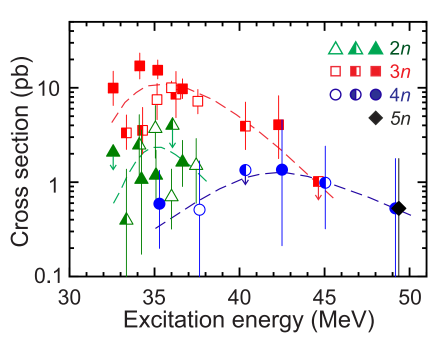

FIG. 2. Cross sections for the $2n$-, $3n$-, $4n$-, and $5n$-evaporation channels for the ^{243}Am + ^{48}Ca reaction. Vertical error bars correspond to total uncertainties. Symbols with arrows show upper cross-section limits. Data are shown by open (from Ref. [14]), half-closed (from Ref. [4]), and closed symbols (from Ref. [3] and this work). The cross sections of nuclei observed at BGS at $E^* = 36$ MeV [13] and assigned by us to the $2n$- and $3n$-evaporation channels, are specified arbitrarily (see the text). The dashed lines through the data are drawn to guide the eye.

created with a fusion of ^{48}Ca beam and actinide target in the process of deexcitation which is largely determined by the fission barriers.

At all the beam energies listed in Table III of the Supplemental Material [11], we registered a total of four decay chains of ^{287}Mc. The doubling of the number of ^{287}Mc chains compared to the known data made it possible to more accurately determine the decay properties of isotopes from ^{287}Mc to ^{267}Db. Compared with the data given in [18], half-lives of ^{287}Mc, ^{279}Rg, ^{275}Mt, and ^{267}Db ($T_{SF} = 1.4^{+1.0}_{-0.4}$ h) practically coincide with the values known earlier. The half-lives of ^{283}Nh and ^{271}Bh turned out to be longer, but the difference does not go beyond statistical uncertainties.

In one of the chains of ^{287}Mc, we registered for the first time the spontaneous fission of ^{279}Rg, which is the third of 26 odd-Z known nuclides with $Z > 105$ and $N > 162$ undergoing SF decay mode. The probability that α decay of ^{279}Rg has not been registered, and the fission belongs to ^{275}Mt, is less than 8% (the probability of registering an α particle exceeds 92%). Moreover, the decrease of the half-life of ^{279}Rg compared to that for ^{281}Rg ($\log_{10}T_{SF}[^{281}\text{Rg}] - \log_{10}T_{SF}[^{279}\text{Rg}]$) would be about 1.3, which is close to similar ratios for odd-N isotopes ^{279}Ds and ^{281}Ds (≈1.8) and even-even ^{282}Cn and ^{284}Cn (≈2.2) [18–20]; see below. Such ratios are in agreement with the predictions of the spontaneous fission half-lives of nuclei, namely, the drop of half-lives with a decrease in the number of neutrons, the reaching the minimum values for nuclei with $N \approx 167-170$, and again the increase of half-lives up to the magic number $N = 162$. We estimated the branch for α decay of ^{279}Rg $b_\alpha = 87^{+5}_{-19}$%; partial half-lives are $T_\alpha = 0.10^{+0.08}_{-0.03}$ s and $T_{SF} = 0.7^{+0.7}_{-0.5}$ s.

In these experiments, products of the $4n$-evaporation channel were observed in the excitation energy range 35−49 MeV. The maximum cross section of $1.4^{+3.2}_{-1.2}$ pb was observed at about 42 MeV.

At an excitation energy of about 35 MeV, we registered 52 new decay chains of ^{288}Mc. As in [3], we observed α activity with $E_\alpha = 7.6$–8.0 MeV between α decays of ^{272}Bh and spontaneous fission events, which we attributed to the isotope ^{264}Lr. The new results made it possible to more accurately determine the half-life of ^{264}Lr ($4.8^{+2.2}_{-1.3}$ h) and the branch for α decay of ^{268}Db (51^{+14}_{-12}%). The increased background of α-like events in this experiment did not allow us to improve the accuracy of the half-life of 16-h ^{268}Db.

With an increase in the number of registered nuclei, α particles with lower energy compared to the energies of the main peaks were observed. For example, the energy of ^{280}Rg in chain 19 (Table I in the Supplemental Material [11]) of 8.10 MeV is smaller than the energy of the main peak by almost 1.7 MeV. In chain 47, the energy of the last of the registered α particles, which may belong to ^{276}Mt or ^{272}Bh, is 7.10 MeV, which differs from the main peaks of these isotopes by 2.5 or 2 MeV, respectively. One cannot exclude that these particles deposited the main part of full energy in the focal detector and escaped from it at a small angle, with the remaining part (1.7−2.5 MeV) lost in its dead layer or missing the side detector. For example, the α particle might be implanted into the gap between the focal and side detectors, see, e.g., Ref. [4]. In test reaction $^{\rm nat}$Yb+ ^{48}Ca, it was found that up to 0.7% of α decays of ^{217}Th deposited in the detector can be detected by a focal detector with energies in the range 6.5−7.8 MeV, which is 1.46–2.76 MeV lower than the energy of the main line of 9.26 MeV. It can be expected that due to the lower implantation depth of Mc isotopes, the fraction of α particles with low energies will be approximately half as low. However, with large a number of obtained Mc chains, it becomes possible to observe a few α decays with incomplete energy deposition.

It can be noted that for none of the nuclei did we find grouping events with specific values $\log_{10}T_\alpha$ vs E_α which would differ from the main bulk of events and which could indicate the observation of isomeric decays in these nuclei.

In this work, we have registered 55 new decay chains of ^{288}Mc. Together with the results of [3–5,13,16], the number of chains of this nucleus has reached about 210. However, in this and previous experiments, the decay chain ER−^{288}Mc (EC/β^+, $T_{1/2} = 0.2$ s)-^{288}Fl ($E_\alpha = 9.9$ MeV, $T_{1/2} = 0.7$ s)-^{284}Cn (SF, $T_{1/2} = 0.1$ s), namely, the product of the electron capture or β^+ decay (EC/β^+) of ^{288}Mc or the $p2n$ channel of the ^{243}Am + ^{48}Ca reaction, was not observed. Only one chain (T2 in [14]) could belong to this channel, however, the total energy of the α particle has not been measured, which does not allow it to be attributed with certainty to ^{288}Fl. Based on this, we can conclude that the probability of EC does not exceed about 0.5% for ^{288}Mc. At the same time, out of 24 short chains observed in the ^{243}Am + ^{48}Ca reaction in [3,4,13,14] and these experiments, nine chains may resemble α decay of ^{288}Mc, followed by EC of ^{284}Nh and spontaneous fission of ^{284}Cn. Unfortunately, predictions of half-lives relative to EC are scarce and the accuracy of theoretical estimates can vary by up to two orders of magnitude depending on the parameters of the models, see, e.g., [21,22]. It should be noted that both nuclides ^{288}Mc and ^{284}Nh are located in the region of nuclei where the predicted lifetimes relative to EC exceed 100 s [23].

We roughly estimated the EC/β^+ half-lives within the independent quasiparticle approximation on the basis of Skyrme energy-density functionals SLy4 and SkO. For these estimates self-consistent calculations of the mean field were first performed by means of a deformed Hartree-Fock-Bogoliubov (HFB) model, for which we used the code HFTHO [24]. This code treats odd nucleons in the HFB ground state through the equal-filling approximation [25]. We performed our calculations on a 20-shell cylindrical transformed deformed harmonic oscillator basis. It is interesting to note that both Skyrme forces, SLy4 and SkO, predict the same ground-state proton-neutron configurations: $1/2^-[510]_p 1/2^+[611]_n$ in ^{288}Mc and $3/2^-[512]_p 1/2^+[611]_n$ in ^{284}Nh, and give close values of the quadrupole deformations: $\beta_2 \approx 0.137$ for ^{288}Mc and $\beta_2 \approx 0.161$ for ^{284}Nh.

When calculating EC/β^+ half-lives, we follow [21] and consider only allowed Gamow-Teller (GT$_+$) transitions. Final states in the daughter nucleus are treated as proton-neutron two-quasiparticle states above the parent HFB ground state. Then, the energy released in the GT$_+$ transition to the nth state in the daughter nucleus is approximated by [26]

$$Q^n_{\rm EC} = \Delta M_{H-n} + \lambda_p - \lambda_n - E_n, \quad Q^n_{\beta^+} = Q^n_{\rm EC} - 2m_e c^2,$$

where ΔM_{H-n} is the hydrogen-neutron mass difference, λ_p and λ_n are the proton and neutron HFB chemical potentials, and E_n is the energy of the two-quasiparticle state. For an odd-odd parent nucleus the lowest E_n value, i.e., E_1, is negative when the g.s. → g.s. transition takes place [27]. In that case $Q^1_{\rm EC}$ corresponds to the electron capture Q value. For ^{288}Mc we obtain $Q^1_{\rm EC} = 4.3$ MeV with Sly4 and $Q^1_{\rm EC} = 5.5$ MeV with SkO, while for ^{284}Nh we have $Q^1_{\rm EC} = 4.5$ MeV with Sly4 and $Q^1_{\rm EC} = 5.0$ MeV with SkO. Note, however, that according to obtained ground-state configurations there are no g.s. → g.s. allowed beta transitions in the considered nuclei.

The resulting half-lives are $T_{EC/\beta^+} = 1.1 \times 10^3$ s (SLy4), 1.0×10^2 s (SkO) for ^{288}Mc, and $T_{\rm EC/\beta^+} = 9.9 \times 10^2$ s (SLy4), 2.0×10^2 s (SkO) for ^{284}Nh. The difference of an order of magnitude between half-lives obtained with two different Skyrme forces has two reasons: (i) SkO parametrization predicts larger weak-decay Q values and (ii) produces a larger effective nucleon mass. The latter leads to a denser quasiparticle spectrum and respectively to a greater number of two-quasiparticle states contributing to EC/β^+ decay. It is worth noting that the simpler calculations performed in [21] lead to $T_{\rm EC/\beta^+} = 4.5$ s for ^{288}Mc and $T_{\rm EC/\beta^+} = 7$ s for ^{284}Nh that are significantly shorter than the obtained results. Present half-lives, however, are consistent with the experimental value of the lower $T_{\rm EC/\beta^+}$ limit of about 40 s for ^{288}Mc and with theoretical estimates of [22] for nuclei in the same mass region.

We also compared the branches $b_{\rm EC}$ with respect to α decay for ^{288}Mc and ^{284}Nh. For this we used the empirical systematic of the EC half-life T_{EC} vs energy Q_β shown in Fig. 9 of Ref. [18], the EC energies from the tables [9,28–31], as well as experimental half-lives (Fig. 1). It follows from these estimates that the b_{EC} branch for ^{284}Nh may be the same as that for ^{288}Mc or up to twice as high, namely, $\leqslant 1\%$. Based on this, it seems unlikely that the nine chains are due to EC of ^{284}Nh and fission of ^{284}Cn.

At this time, there is no clear understanding of the origin of the short chains. Apparently, only a direct measurement of the mass number of one of the isotopes in the short chain will dispel doubts, e.g., using the devices presented at [16,32]. As can be seen in Fig. 2, the production cross sections of the short chains, which we tentatively assign to ^{289}Mc, are somewhat grouped at lower excitation energies. In [16], 46 chains were published; the duration of decays of three of them is significantly shorter than that of chains which were presumably assigned by the authors to ^{288}Mc. Since the reaction cross section is not given in [16], we tentatively equated the cross section for the 43 long chains to 10 pb, and the remaining three to 0.7 pb (10*3/43).

The 2n-evaporation channel was unambiguously observed in the ^{245}Cm + ^{48}Ca reaction [18,33]. In this case, the values of the cross sections for the 2n and 3n channels are consistent with each other within the measurement errors at energies of 33 and 38 MeV. The results of calculations [34,35] also indicate that the energy maxima of the cross sections of the 2n and 3n channels of the ^{243}Am + ^{48}Ca reaction coincide with each other. In [36,37], the maximum of the 3n channel is shifted by 2–3 MeV relative to that of the 2n channel. The location of the maximum of the 2n channel is 7–9 MeV less than that for the 3n channel in [38–40], however, in the same calculations, the locations of the same channels for the ^{245}Cm + ^{48}Ca reaction are also shifted relative to each other by 6–10 MeV, which is not consistent with the results of the experiment [18,33]. Thus, the results of calculations of the excitation function of the ^{243}Am + ^{48}Ca reaction do not allow us to draw definitive conclusions.

The decay times of the parent and daughter nuclei in the long and short chains are close to each other, but the half-lives are definitely different and the uncertainties (for a confidence level of 68%) do not overlap (Fig. 1).

It should be noted that the probability of fission of nuclei with an odd number of neutrons (^{288}Mc and ^{284}Nh) should be less compared to nuclei with an even N (^{289}Mc and ^{285}Nh).

Finally, the pattern of the decay chain of ^{293}Ts, the product of the ^{249}Bk(^{48}Ca, 4n) reaction, coincides well with the pattern of decay in the short chain observed in the ^{243}Am + ^{48}Ca reaction.

We add that the statement that the "cross-reaction link between α-decay chains associated with the isotopes ^{293}117 and ^{289}115 is highly improbable" [41] was based on the misleading method used to analyze the decay times of nuclei; see [42].

Nevertheless, we cannot completely exclude that short chains originate from another branch of the decay of ^{288}Mc, but we believe that assignment of the short chain to ^{289}Mc seems more realistic. Further discussions will be based on this interpretation.

In experiments on the synthesis of element Ts in the ^{249}Bk + ^{48}Ca reaction at DGFRS, α decay of ^{285}Nh was not observed in two of the 16 chains of ^{293}Ts [12], but it was registered in both chains obtained at TASCA [15]. In the ^{243}Am + ^{48}Ca reaction, α decay of ^{285}Nh was found in all four chains at DGFRS [4], but in two of the seven chains obtained at TASCA and in two of the three chains at BGS [13,14], ^{285}Nh was not observed. From the analysis of results of [4,13,14] it was concluded that there is a 29% branch for SF of ^{285}Nh [14]. In [3] and this paper (see Table II of the Supplemental Material [11]) we also did not observe α decay of ^{285}Nh in half of the ten chains. Thus, α decay of ^{285}Nh has not been registered in 11 of the 42 chains, which cannot be due to the limited registration efficiency of detector. At the same time, in two of these 11 ER-α-SF chains (see Refs. [3,14] and this work), the total α-particle energy was not recorded, which does not allow them to be attributed with confidence to ^{289}Mc. In eight such chains, the α-particle energy at least exceeds 10.1 MeV which corresponds to the energy interval for ^{289}Mc. From the set of these data, it follows that ^{285}Nh has a branch for SF of $18^{+10}_{-9}\%$, which does not contradict the result of [14]. We estimated the partial half-lives of $T_\alpha = 2.6^{+0.7}_{-0.5}$ s and $T_{SF} = 12^{+12}_{-5}$ s for ^{285}Nh. We also estimated an α-decay branch for the daughter nucleus ^{281}Rg of $14^{+10}_{-4}\%$ with partial half-lives of $T_\alpha = 79^{+42}_{-34}$ s and $T_{SF} = 13^{+4}_{-2}$ s.

We attribute all observed fission fragments to spontaneous fission of the corresponding nuclei. Although it has been shown that the probability of EC for ^{288}Mc is less than 0.5% and for ^{284}Nh apparently does not exceed 1%, it should be noted that the contribution of this decay mode for odd nuclei is not completely excluded. This may be especially true for light odd-odd nuclei at the end of the observed chains. Electron capture in these nuclei leads to even-even nuclei, for which relatively rapid spontaneous fission is expected to be quite likely. The future experimental and theoretical study of this issue presents a serious challenge.

The partial SF half-life of ^{279}Rg measured for the first time in this work, along with the refined values for the isotopes ^{264}Lr, $^{266-268}$Db, ^{281}Rg, ^{285}Nh, are shown in Fig. 3. The remaining experimental data are taken from the reviews [18,44] and Refs. [3,19,20,45]. The gray area shows the half-life interval predicted in [43] for even-even nuclei with $Z = 104-110$, $N = 160$–164 and $Z = 110$–114, $N = 164$–177. The model predictions for even-even isotopes are in good agreement with experimental data for ^{280}Ds, ^{282,284}Cn, and ^{286}Fl. It is interesting to note that predictions [43] were published in 1999, when the region of superheavy nuclei was completely unknown.

All other odd-Z and/or odd-N nuclei have half-lives noticeably higher than the specified region, which may be naturally caused by the presence of hindrance factors (HFs) on the probability of their spontaneous fission. The values for the odd-Z nuclei do not seem unreasonable. From the presented data, it is possible to extract from experimental values, and not from comparisons with calculated ones, the hindrance factors for SF for odd-N isotopes of elements Ds and Cn using the

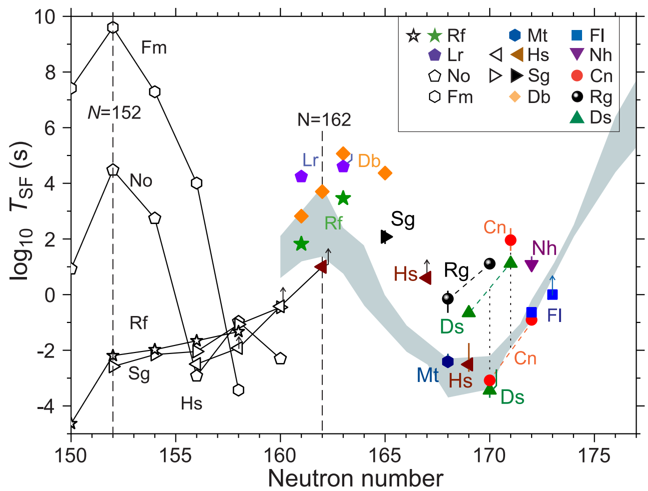

FIG. 3. Common logarithm of partial spontaneous fission half-life [$\log_{10}(T_{SF}[s])$] vs neutron number for isotopes of elements with $Z = 100-114$. The area of half-lives of even-even isotopes with $Z = 104-110$, $N = 160–164$ and $Z = 110–114$, $N = 164–177$ predicted in [43] is highlighted in gray. Partial half-lives of nuclei produced in the ^{48}Ca -induced reactions with actinide targets are shown by filled symbols.

ratios

$$\log_{10}\mathrm{HF} = \{\log_{10} T_{SF}(^{279}\mathrm{Ds}) + \log_{10} T_{SF}(^{281}\mathrm{Ds})\}/\{2\log_{10} T_{SF}(^{280}\mathrm{Ds})\} = 3.66$$

and

$$\log_{10}\mathrm{HF} = 2\log_{10} T_{SF}(^{283}\mathrm{Cn})/\{\log_{10} T_{SF}(^{282}\mathrm{Cn}) + \log_{10} T_{SF}(^{284}\mathrm{Cn})\} = 3.95.$$

As a result of experiments ([3,19] and this work) performed at the new separator DGFRS-2, new data were obtained on the SF half-lives for three isotopes ^{264}Lr, ^{268}Db, and ^{279}Rg, as well as updated data for four odd-Z ^{266,267}Db, ^{281}Rg, ^{285}Nh and eight even-Z ^{286,287}Fl, ^{282,283}Cn, ^{279}Ds, ^{275}Hs, ^{271}Sg, ^{267}Rf.

As shown in Fig. 3, the results of the calculations [43] for even-even isotopes ^{280}Ds, ^{282,284}Cn, and ^{286}Fl agree well with experimental data. The same figure shows the partial SF half-lives for other nuclei with an odd number of protons and/or neutrons, which were produced in the reactions of ^{48}Ca with the nuclei of actinide elements. To compare the results of calculations with these nuclei having certain N and Z, we calculated the unhindered SF half-lives as the geometrical mean of the fission half-lives T_{SF} of the neighboring even-even nuclei as

$$T_{SF}(N, Z) = \{T_{SF}(N-1, Z-1)\times T_{SF}(N+1, Z-1) \times T_{SF}(N-1, Z+1)\times T_{SF}(N+1, Z+1)\}^{1/4},$$

for odd-odd isotopes,

$$T_{SF}(N, Z) = \{T_{SF}(N-1, Z) \times T_{SF}(N+1, Z)\}^{1/2},$$

for odd-N and even-Z isotopes, and

$$T_{SF}(N, Z) = \{T_{SF}(N, Z-1) \times T_{SF}(N, Z+1)\}^{1/2},$$

for even-N and odd-Z isotopes.

The comparison of experimental SF half-lives for different nuclei with several predictions [21,43,46–51] is given in Table II. To obtain better agreement of the predictions [43] with the experimental data, we applied a hindrance factor of 10^2 for odd-A and odd-odd isotopes. In this case, the best agreement with the experiment is obtained. The average differences (ADs) of the corrected for HF theoretical predictions $\log_{10}T_{SF}$ (calc) from experimental data $\log_{10}T_{SF}$ (expt) is closest to 0, and the standard deviation (SD = 1.27) is the lowest compared to other models. For even-even nuclei corresponding values are AD = 0.640 and SD = 0.245.

For another model [46], also macroscopic-microscopic and published in 1995, a good agreement of the predictions with the experiment is also achieved if we use hindrance factors of 10 and 10^3 for odd-A and odd-odd isotopes, respectively. Note that for all models, we calculated individual deviations of the theory (for unhindered half-lives) from the experiment for different nuclei (odd-odd, odd Z, odd N), and then introduced appropriate hindrance factors. For even-even nuclei, this model results in a somewhat larger AD = 1.45 but relatively low SD = 0.464.

The table also provides a comparison of experimental results with self-consistent calculations performed in the Hartree-Fock-Bogoliubov (HFB) approach with the D1S Gogny force [47]. If we apply a hindrance factor of 10 for odd-odd isotopes, the AD of 1.06 will be obtained but with a relatively large SD of 2.38. This model predicts systematically longer T_{SF} for even-even nuclei, AD = 3.30, SD = 1.74.

Other self-consistent Skyrme-HFB calculations [48] have larger differences from the experiment for even-even nuclei, on average six orders of magnitude lower (AD = −6.04, SD = 1.88). All data for this model are given without adding a hindrance factor.

Recently, a new cluster approach was developed and applied for calculating the SF half-lives of even-Z nuclei [49]. The SF process is described in terms of the dinuclear system (DNS) model and considered as the evolution of a nucleus in collective charge asymmetry coordinates. The DNS states responsible for the SF correspond to the minima of the DNS potential energy as a function of charge asymmetry. These states are fully described with the stationary Schrödinger equation. For even-odd nuclei the origin of the SF hindrance comes from the DNS potential energy changes which are strongly related to the spin of the nucleus considered. The calculations reproduce the experimental data quite well. The AD value is only −0.22, and the SD of 1.15 is the lowest of all those given in the table. Note that the hindrance factor was not applied, although 8 of the 12 values belong to odd-N nuclei.

In addition to the mentioned models, we present in the table the results of calculations of SF half-lives of given nuclei using a number of phenomenological formulas [21,50,51]. These formulas are based on the idea by Swiatecki [52] who suggested a simple relation between the SF half-lives and the deviations of experimental mass from their liquid-drop

TABLE II. Comparison of experimental partial spontaneous fission half-lives (common logarithm) for nuclei with certain $^{A}Z_{N}$ with predictions [21,43,46–51]. Average differences AD of theoretical predictions $\log_{10}T_{SF}$ (calc) from experimental data $\log_{10}T_{SF}$ (expt), as well as standard deviations SD of these values are given at the bottom of table for each model.

	$\mathrm{Log}_{10}T_{SF}$(s)								
Isotope	Expt.[a]	[46][b]	[43][c]	[47][d]	[48][e]	[49]	[21]	[50]	[51]
^{264}Lr$_{161}$	4.24	4.24	4.15	4.28			7.30	7.58	1.97
^{266}Lr$_{163}$	4.60		6.15	2.82			8.53	7.93	0.269
^{266}Db$_{161}$	2.82	5.91	4.07	7.07			6.62	7.21	2.09
^{268}Db$_{163}$	5.07	5.84	3.27	5.87			8.06	7.96	1.13
^{270}Db$_{165}$	4.37	3.91	1.37	1.52			6.00	5.17	−1.24
^{267}Db$_{162}$	3.70	3.73	4.60	7.33			8.30	5.22	1.68
^{277}Mt$_{168}$	−2.41	−0.295	−0.951	0.265	−5.18		1.25	−2.73	−1.96
^{279}Rg$_{168}$	−0.148	−0.360	−0.751	2.41	−4.93		0.104	−2.95	−0.110
^{281}Rg$_{170}$	1.12	−0.535	−0.551	−1.12	−8.09		1.51	−1.89	−0.935
^{285}Nh$_{172}$	1.09	1.39	1.60	3.68	−8.34		3.16	3.04	1.40
^{265}Rf$_{161}$	1.82	1.88	3.15	4.61		1.99	6.98	4.06	1.86
^{267}Rf$_{163}$	3.46	1.76	2.45	3.24		2.85	8.27	4.59	0.547
^{271}Sg$_{165}$	2.08	1.60	1.35	1.81		2.63	5.74	1.81	−0.796
^{275}Hs$_{167}$	>0.602	0.713	0.249	0.625	−4.36	1.22	2.51	−1.52	−1.71
^{277}Hs$_{169}$	−2.51	−1.17	−1.10	−2.63	−6.85	−2.80	1.16	−3.49	−3.93
^{279}Ds$_{169}$	−0.658	−0.0862	−1.05	−0.020	−6.16	−0.96	0.691	−3.12	−1.63
^{281}Ds$_{171}$	1.12	0.127	0.0991	−1.37	−8.90	−0.72	2.07	−2.14	−2.94
^{283}Cn$_{171}$	1.95	0.727	0.599	1.05	−8.59	−0.54	2.95	0.317	0.0724
^{280}Ds$_{170}$	−3.44	−1.92	−2.90	−1.98	−7.53	−2.39	−1.09	−6.24	−2.40
^{282}Cn$_{170}$	−3.08	−1.15	−2.20	−0.270	−8.03	−1.69	−0.131	−3.78	0.289
^{284}Cn$_{172}$	−0.910	0.602	−0.0601	2.36	−9.15	−1.34	1.74	−2.15	−0.645
^{286}Fl$_{172}$	−0.638	0.176	−0.201	5.00	−7.53	−0.25	3.40	1.54	3.05
AD		0.166	−0.0491	1.06	−6.73	−0.22	2.81	0.204	−1.23
SD		1.28	1.27	2.38	2.66	1.15	1.45	2.39	2.39

[a]References are given in the text.
[b]Hindrance factors of 10 and 10^3 were applied for odd-A and odd-odd isotopes, respectively. AD value $\log_{10}T_{SF}$ (calc) - $\log_{10}T_{SF}$ (expt) and SD for even-even nuclei are 1.45 and 0.464, respectively.
[c]Hindrance factor of 10^2 was applied for odd-A and odd-odd isotopes. AD = 0.640 and SD = 0.245 for even-even nuclei.
[d]Hindrance factor of 10 was applied for odd-odd isotopes. AD = 3.30 and SD = 1.74 for even-even nuclei.
[e]Hindrance factor was not applied. AD = −6.04 and SD = 1.88 for even-even nuclei.

estimates (shell correction energy). Note that the hindrance factors in the formulas are either already taken into account [21,50] or are not used [51].

Formula [21] gives results that exceed experimental data by almost three orders of magnitude (AD = 2.81), but has a noticeably smaller variation in deviations between calculated and experimental values (SD = 1.45). On the contrary, the results of later suggested formulas [50,51] are much closer to the experiment (AD = 0.204 and −1.23, respectively), but have a larger spread in deviations (SD = 2.39).

In addition, Swiatecki-like systematics of SF half-lives have recently been proposed in [53]. It was shown that the simple one-dimensional WKB model reproduces the measured lifetimes quite well, within several orders of magnitude, for even and odd nuclei up to $Z = 102$, as well as for even-even nuclei from Th to Ds.

Summarizing, one can conclude that T_{SF} calculations based on macroscopic-microscopic models, which were published about a quarter of a century ago, still reproduce experimental data for nuclei obtained in the ^{48}Ca-induced reactions better than later self-consistent models, even though the self-consistent models are based on realistic effective interactions. In addition, calculating the SF half-lives of nuclei with odd N and/or Z within these models still remains a great challenge.

Simplified formulas can reproduce with some accuracy the half-lives of nuclei even with odd numbers N and/or Z. However, these formulas do not take into account the variety of mechanisms that determine nuclear fission.

IV. CONCLUSION

A second series of experiments on the study of the ^{243}Am + ^{48}Ca reaction was carried out at the gas-filled separator DGFRS-2 online to the DC280 cyclotron at the SHE Factory at JINR. The reaction was studied at three projectile energies of 242, 250, and 259 MeV.

At maximum energy, a new lightest isotope ^{286}Mc with an α-particle energy of 10.71 ± 0.02 MeV and a half-life of 20^{+98}_{-9} ms was synthesized for the first time. The cross section of the $5n$-evaporation channel was $0.5^{+1.3}_{-0.4}$ pb. This value is close to those that were determined in the ^{244}Pu (^{48}Ca, $5n$) ^{287}Fl [7] and ^{242}Pu (^{48}Ca, $5n$) ^{285}Fl [8] reactions when observing one chain in each of the reactions.

At all three energies, four new decay chains of ^{287}Mc were registered, which made it possible to measure the excitation function of the reaction in a wide energy range. Spontaneous fission of ^{279}Rg was observed for the first time in one of the chains; its partial half-lives were established to be $T_\alpha = 0.10^{+0.08}_{-0.03}$ s and $T_{\mathrm{SF}} = 0.7^{+0.7}_{-0.5}$ s.

At the two lowest ^{48}Ca energies, 55 new ^{288}Mc chains were obtained. The results confirmed the existence of an approximately 50% α decay branch for ^{268}Db, which leads to the spontaneously fissioning ^{264}Lr observed in the first series of experiments at DGFRS-2 [3].

The origin of four additionally observed short ER- α-(α)-SF chains is discussed based on the cross sections of their formation and the properties of all nuclei in the chains. It is concluded that they are more likely to be attributed to ^{289}Mc, but for the final solution of this issue, it is necessary to measure the mass number of at least one of the nuclei in the chain.

The decay properties of 21 previously known odd-Z isotopes were determined with higher precision. Seven of them partially or completely decay by spontaneous fission. The partial half-lives of nuclei synthesized in the reactions of actinide targets with ^{48}Ca are compared with predictions within several models or based on simplified formulas similar to the Swiatecki model. The expanded database for the fission half-lives of very heavy nuclei still points to fact that the understanding of the fission mechanism requires further theoretical and experimental attention.

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