Synthesis of superheavy nuclei in ^{48}Ca-induced reactions

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This paper presents results of experiments aimed at producing long-lived superheavy elements located near the spherical shells at Z≥ 114 and N≥ 172 in the reactions of neutron-rich isotopes ^{242,244}Pu, ^{243}Am, ^{245,248}Cm and ^{249}Cf with ^{48}Ca projectiles. The decay properties of the synthesized nuclei are consistent with the consecutive α-decays originating in the decays of parent nuclides ^{286,287,288,289}114, ^{287,288}115, ^{290,291,293}116 and ^{294}118 produced in the 2n- to 5n-evaporation channels. The present observations can be considered to be experimental evidence of the existence of the "island of stability" of superheavy elements

Introduction

The stability of heavy nuclei is largely determined by nuclear shell structure whose influence is considerably increased near closed proton Z and neutron N shells. Beyond the domain of the heaviest known nuclei, the nuclear macroscopic-microscopic theory predicts the existence of an "island of stability" of long-lived superheavy elements. Calculations performed over more than 35 years with different versions of the nuclear shell model predict a substantial enhancement of the stability of heavy nuclei when approaching the closed spherical shells Z=114 and N=184, the next spherical shells after ^{208}Pb (Z=82 and N=126). Superheavy nuclei close to the predicted magic neutron shell N=184 can be synthesized in complete fusion reactions of target and projectile nuclei with significant neutron excess. With the doubly magic ^{48}Ca projectile, the resulting compound nuclei should have an excitation energy of about 27÷33 MeV at the Coulomb barrier. Correspondingly, nuclear shell effects are still expected to persist in the excited nucleus, thus increasing the survival probability of the evaporation residues (ER), as compared to "hot fusion" reactions ($E^* \approx 45$ MeV), which were used for the synthesis of heavy isotopes of elements with atomic numbers Z=106, 108 and 110 (see, e.g., [1), 2)]). Additionally, the high mass asymmetry in the entrance channel should decrease the dynamical limitations on nuclear fusion that arises in more symmetrical reactions. Our present experiments were designed

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to attempt the production of elements 114, 115, 116, and 118 in the reactions of ^{242,244}Pu, ^{243}Am, ^{245,248}Cm, and ^{249}Cf with ^{48}Ca at the picobarn cross-section level, thus exceeding the sensitivity of the previous experiments by at least two orders of magnitude.

§1. Experimental Technique

A beam of ^{48}Ca ions was delivered by the U400 cyclotron at FLNR, JINR. The typical intensity of the continuous ion beam on the target was $\sim$ 1.2 pμA. The beam energy was determined with a precision of 1 MeV by measuring the energies of scattered ions, and by a time-of-flight technique. The rotating targets contained the enriched isotopes ^{242}Pu (99.9%), ^{244}Pu (98.6%), ^{243}Am (99.9%), ^{245}Cm (98.7%), ^{248}Cm (97.4%), and ^{249}Cf (97.3%) deposited onto 32-cm^2 of 1.5-μm Ti foils to a thickness of $\sim$ 0.35 mg·cm^{-2}.

The evaporation residues recoiling from the target were spatially separated in flight from the beam, scattered particles and transfer reaction products by the Dubna Gas-filled Recoil Separator (DGFRS) [3]. The recoils passed through the hydrogen-filled volume of the separator (1 Torr), a Mylar window ($\sim$ 1 μm), then through a time-of-flight (TOF) system filled by pentane ($\sim$ 1.5 Torr), and were finally implanted in the focal-plane detector array. The transmission efficiency of the separator for Z=114-118 nuclei was estimated to be about 35-40% [3].

The focal-plane detector consisted of three 4 $\times$ 4 cm^2 silicon detectors, each with four strips having position sensitivity in the vertical direction. To increase the detection efficiency for full-energy α's, we arranged 8 detectors without position sensitivity in a box surrounding the focal-plane detector. Employing side detectors, the α-particle detection efficiency increased from 53% to 87%.

Alpha-energy calibrations were performed using the peaks from nuclides produced in the bombardments of ^{nat}Yb and enriched $^{204,206-208}$Pb targets with ^{48}Ca ions [4]. The energy resolution for the detection of particles in the focal-plane detector was about 60-90 keV. For α's escaping from the focal-plane detector at different angles and absorbed in the side detectors, the energy resolution was 140-200 keV because of energy losses in the entrance windows and dead layers of both detectors and the pentane. The FWHM position resolutions of the signals of correlated decays of nuclei implanted in the detectors were 0.8-1.3 mm and 0.5-0.8 mm for ER-α and ER-SF signals, respectively. Fission fragments from ^{252}No implants produced in the ^{206}Pb+^{48}Ca reaction were used for a fission-energy calibration. The measured fragment energies were not corrected for the pulse-height defect of the detectors, energy loss in the detectors' entrance windows, dead layers, or the low-pressure pentane gas filling the detection system. The mean sum energy loss of fission fragments for ^{252}No was about 20 MeV.

In many of the experiments, we used a special detection mode for registering two or more sequential decays. The beam was switched off after a recoil signal was detected with parameters of implantation energy and TOF expected for the evaporation residues, followed by an α-like signal within a preset energy and time interval, in the same strip, within a position window that corresponded to the position resolution. Thus, all the expected sequential decays of the daughter nuclides should be observed in the absence of beam-associated background.

§2. Experimental Results

The ^{244}Pu+^{48}Ca bombardments were performed in 1998 and 1999 [5]. A total of 1.5×10^{19} ^{48}Ca projectiles of energy $\sim$ 236 MeV was delivered to the target. Taking into account the energy losses in the target and the overall beam energy and target thickness variations, we expected the resulting compound nuclei ^{292}114 to have excitation energy range $E^* = 32.9 - 37.4$ MeV [6].

According to the concept of the "island of stability" of superheavy elements, as long as any α-decay chain leads to the edge of the stability region, it should be terminated by spontaneous fission (SF) [7]. Two such SF events were observed in strips 2 and 8 [5]. The full decay chains including these two fission events are shown in Fig. 1.

The formation of the nuclei which initiated the observed decays resulted from instantaneous ^{48}Ca beam energies of 237.6 and 237.0 MeV in the middle of the target, corresponding to excitation energy ranges $E^* = 33.6 - 39.7$ and 33.2-39.1 MeV for the ^{292}114 compound nuclei, respectively. This would favor de-excitation of ^{292}114 by evaporation of 3 or 4 neutrons, which leads to the nuclei ^{289}114 or ^{288}114, respectively. The detected sequential decays have $T_{1/2}$ vs. E_α values that correspond well to the allowed α-decays of the isotopes of elements 114 and 112. To illustrate this, Fig. 1 presents the expected half-lives corresponding to the measured α-particle energies for the genetically related nuclides with the specified atomic numbers. For the calculation of half-lives with given Q_α values, the formula by Viola and Seaborg with parameters fitted to the T_α values of 65 known even-even nuclei with Z>82 and N>126 has been used. The measured total deposited energies for both fission events exceed the average value measured for ^{252}No by about 40 MeV, which also indicates the fission of a rather heavy granddaughter nucleus. From the above considerations, one could conclude that the detected decay chains originate from the parent even-even nuclide ^{288}114.

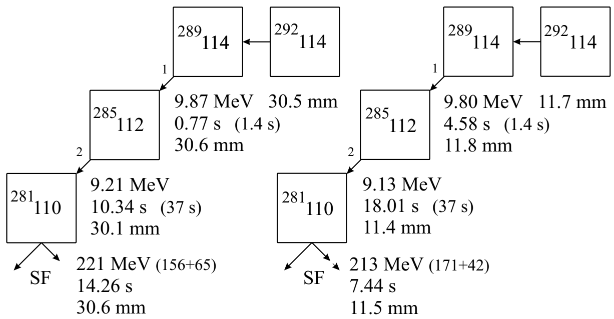

Fig. 1. Time sequences in the observed decay chains [5]. The expected half-lives corresponding to the measured E_α values for the given isotopes are shown in parentheses following the measured lifetimes.

However, in recent experiments, we have measured excitation functions of the reactions ^{244}Pu(^{48}Ca, 3-5n) [8]. In these series of experiments, we chose the bombarding energies for ^{48}Ca ions of 243, 250 and 257 MeV in the middle of the target (E^* = 38.9-43.0 MeV, 44.9-49.0 MeV and 50.4-54.7 MeV, respectively). Corresponding accumulated beam doses were 4.0×10^{18}, 3.1×10^{18} and 2.9×10^{18}. At the ^{48}Ca energy of 243 MeV, we observed two decay chains each consisting of two consecutive decays terminated by SF. Identical decay chains were previously discovered in the same reaction at lower energy of 236 MeV [5]. One more event of this type was detected at the beam energy of 250 MeV. In addition to these decay chains, two new isotopes of element 114 and their descendant nuclei were identified for the first time in this experiment with $E_\alpha = 9.95$ MeV, $T_{1/2} = 0.63$ s and $E_\alpha = 10.04$ MeV, $T_{1/2} = 1.1$ s. The excitation functions for producing various nuclei in the ^{244}Pu+^{48}Ca are shown in Fig. 2. Surprisingly enough, the decays with $E_\alpha = 9.95$ MeV and $T_{1/2} = 0.63$ s correspond well also to the allowed α-decays of the isotope of element 114 and the corresponding excitation function (shown in Fig. 2 by circles) is similar to what could be expected for the 4n-evaporation channel of the reaction ^{244}Pu+^{48}Ca.

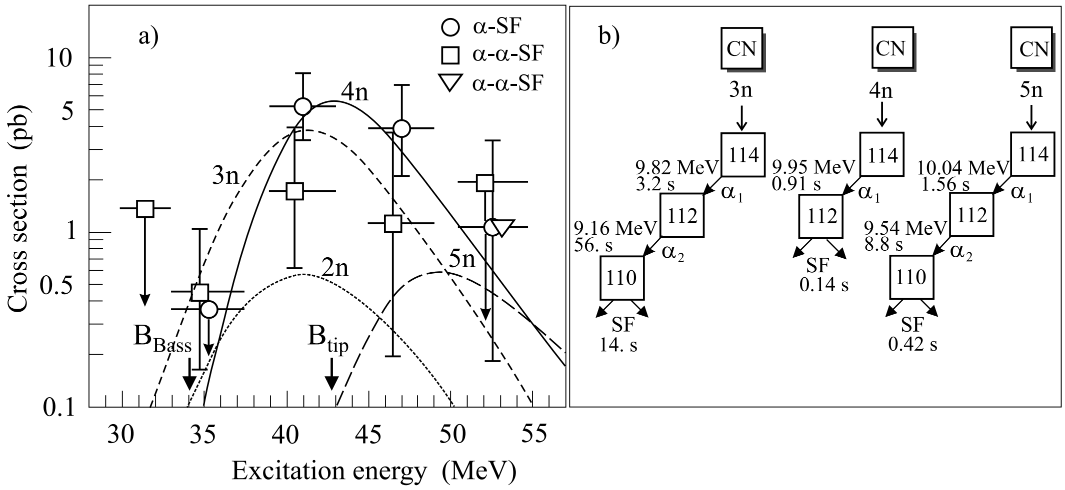

Fig. 2. a) Excitation functions for the 3n (□), 4n (◯), and 5n (▽) evaporation channels from the ^{244}Pu+^{48}Ca fusion reaction. Error bars correspond to statistical uncertainties. The Bass barrier [9] and the barrier of tip orientation are shown by the arrows. The curves show the results of calculations for the cross sections of 2n - 5n ER channels [10]. b) Decay chains of isotopes ^{287,288,289}114 observed in the experiment [8]. Average α-particle energies and lifetimes are shown.

Based on the results of these experiments, it was reasonable to assign previously observed ER-α-α-SF chain [5] to the decay of even-odd nuclide ^{289}114 produced via 3n-evaporation with the maximum cross section of about 1.7 pb. Then the two other nuclei should be assigned to the decay of neighboring even-even and even-odd isotopes of element 114, ^{288}114 and ^{287}114, produced in 4n- and 5n-evaporation channels with the cross sections of 5.3 pb and $\sim$1 pb, respectively [8].

Considering the mass-number identification, one can note that a more solid mass identification is possible if the mass number of the target nucleus can be varied. Thus, if suggested mass assignment is correct, the isotope ^{287}114 should be observer in 3n-evaporation channel of the reaction ^{242}Pu+^{48}Ca and another even-even isotope ^{286}114 with higher α-particle energy and lower life-time should be produced via 4n-evaporation.

Indeed, in the experiments started on September 18, 2003 and aimed at the cross section measurement of reactions ^{242}Pu(^{48}Ca,xn)$^{290-x}$114, we observed two isotopes ^{287}114 and ^{286}114 [11]. The typical decay chains of these isotopes are shown in Fig. 3. The decay properties of nuclei originating from ^{287}114 produced in the ^{242}Pu+^{48}Ca reaction coincide well with those for nuclei observed in the ^{244}Pu(^{48}Ca,5n)^{287}114 reaction. The even-even isotope ^{286}114 undergoes SF and α decay with $T_{1/2} = 0.17$ s, while ^{282}112 decays by SF with $T_{SF} = 0.52$ ms.

In view of the new interpretations, the data of our first experiments [12] performed at low excitation energy ($E^* =$ 35 MeV) needs further analysis. In the recent ^{244}Pu+^{48}Ca experiment [8], at $E^* = 41 - 53$ MeV as well as in the previous experiment [5] at $E^* = 35$ MeV, we did not observe the long decay chain similar to that which we had detected in our first experiment [12] which was interpreted as a *candidate* for the decay of ^{289}114. The cross section corresponding to this single event was estimated to be about 0.2 pb. One could propose that this chain originates from the decay of the neighboring isotope ^{290}114 produced via 2n-evaporation. Indeed, the energy of the first α-particle (9.71 MeV) is about 0.1 MeV lower than that of the isotope ^{289}114 assigned from our most recent work [8] and the energies of the next two α-particles (8.67 MeV and 8.83 MeV) do not contradict what is expected for ^{286}112 and ^{282}110. Yet in this case, one has to suppose a considerable increase in stability against decay by SF of these nuclei compared with the even-even neighbors, i.e., ^{284}112 ($T_{SF} \approx 0.1$ s). On the other hand, some calculations [13] show that such a long chain can be assigned to a rare decay branch of the even-odd nuclide ^{289}114. This rare decay starts from the first excited state rather than from the ground state and goes through low-lying levels in the daughter nuclei in accordance with the selection rules associated with the appropriate quantum numbers.

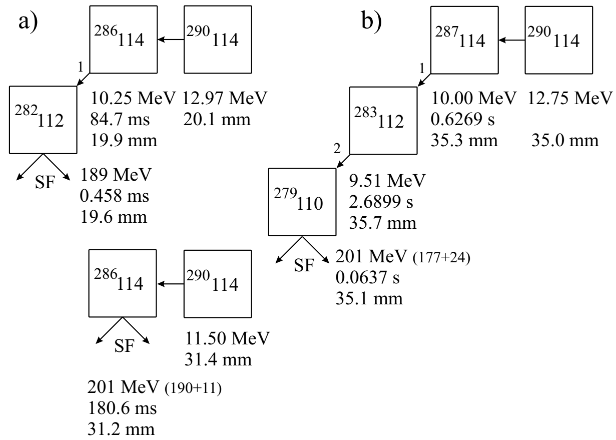

Fig. 3. Typical decay chains observed in the reactions ^{242}Pu(^{48}Ca,3,4n)^{286,287}114 [11].

In our experiments, we did not observe the 3-minute α-SF decay chain that was earlier reported from the experiments performed with the VASSILISSA separator in the ^{242}Pu+^{48}Ca reaction, also at low excitation energy of the compound nucleus ^{290}114 ($E^* = 32.6$ MeV) and ascribed to ^{287}114 [14]. This could also be a less probable decay mode, yet this discussion is based on only a few events, which were observed in the first experiments.

Together with cross section measurements, the other approach for the mass and atomic-number identification of unknown nuclei, e.g., cross bombardments, was widely applied in previous experiments. In our case this would means the production of the same isotopes of element 114 as daughter nuclei following decays of heavier mother nuclei with Z=116.

For the first time this method was used in our experiment aimed at the synthesis of superheavy nuclei with Z=116 in the complete fusion reaction ^{248}Cm+^{48}Ca [15)] in 2000-2001. In this experiment, three similar decay sequences were observed. The implantation of ERs in strips 4, 5, and 1 were followed by α-particles with $E_\alpha = 10.53$ MeV. All the decays following the first particles agree well with the decay chains of ^{289}114, previously observed in the ^{244}Pu+^{48}Ca reaction [5), 8)]. Thus, it was reasonable to assign the observed decays to the nuclide ^{293}116, produced via evaporation of three neutrons in the complete-fusion reaction ^{248}Cm+^{48}Ca with a cross section of 0.5 pb.

During March-May, 2003, we carried out an experiment aimed at the investigation of radioactive properties of other isotopes of element 116 in the reaction ^{245}Cm+^{48}Ca. The excitation energy of the compound nucleus at the Coulomb barrier of the ^{245}Cm+^{48}Ca reaction is about 4 MeV lower than in the reaction ^{244}Pu+^{48}Ca. The maximum yield of Z=116 nuclides can be expected in 2n- and 3n-evaporation channels. Therefore, for the reaction ^{245}Cm+^{48}Ca we chose the beam energy of 243 MeV in the middle of the target ($E^* = 30.9 - 35.0$ MeV) at which the production of isotopes ^{260,261}116 is expected with high probability.

In this experiment, with an accumulated beam dose of 1.2×10^{19}, we detected five decay chains which fall into two decay types shown in Fig. 4 [8)]. The first type of decay represents a two- or three-step decay (ER-α-SF or ER-α-α-SF), lasting $\sim$0.5 s. In two of the three decay chains of this type, the first decay was not observed. The probability of detecting the preceding ERs as random events producing an accidental correlation was only about 2% in both cases. Despite the fact that the α-particles were not observed, we tentatively assigned these events to the same type, supposing that the α-particles were not detected. In this experiment, we registered eight α-particles by means of a detector with an 87% efficiency. Missing two α-particles is not improbable. The second decay type included three sequential decays and also ended in spontaneous fission. The total time interval between the ER and the SF for that decay type is about 10 s and is dominated by the last α-decay that precedes the SF.

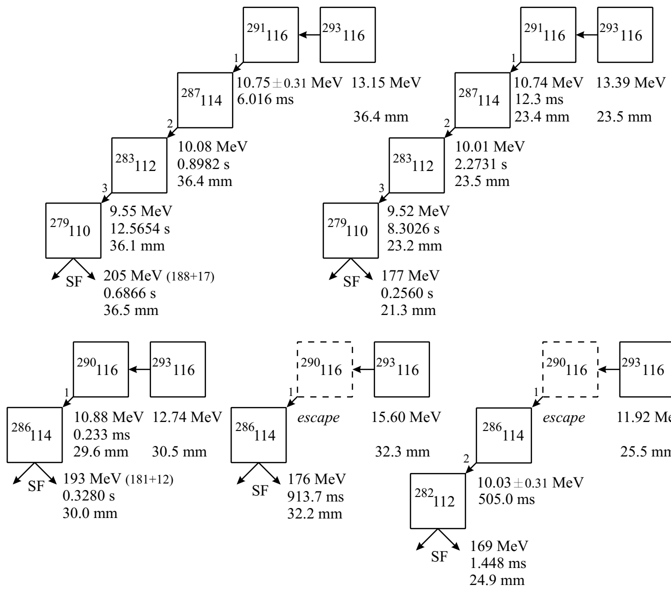

Fig. 4. Time sequences in the decay chains observed in the ^{245}Cm+^{48}Ca reaction [8)].

The decay energies and half-lives agree well when one considers the daughter nuclei in ER-α-α-α-SF decay chains observed in the ^{245}Cm+^{48}Ca reaction together with the chains observed in the reactions ^{244}Pu+^{48}Ca at maximum beam energy $E^* = 53$ MeV (Fig. 2) and ^{242}Pu+^{48}Ca at $E^* = 32.5-40.2$ MeV (Fig. 3b), which were assigned to the decay of ^{287}114, the 5n- and 3n-evaporation products, respectively [5),11)]. Then the longer ER-α-α-α-SF chains observed in the ^{245}Cm+^{48}Ca case should be referred to the decay of ^{291}116 produced via 2n-evaporation. Accordingly, here the shorter chains should be assigned to the even-even ^{290}116, the product of 3n evaporation, because the decay properties of descendant nuclei agree with those of ^{286}114 and ^{282}112 observed in the reaction ^{242}Pu+^{48}Ca at $E^* = 40.2$ and 45.1 MeV [11)] (see Fig. 3a). In the ^{245}Cm+^{48}Ca reaction, the 2n- and 3n-evaporation channels were observed with cross sections of about 0.9 pb and 1.3 pb, respectively.

During February-June, 2002, we carried out an experiment aimed at the synthesis of element 118 in the ^{249}Cf+^{48}Ca reaction [16)]. The excitation energy of the compound nucleus at the Coulomb barrier of this reaction is about 6.3 MeV lower than in the reaction ^{244}Pu+^{48}Ca, thus the maximum yield of Z=118 nuclides could be expected in 2n- and 3n-evaporation channels. A beam dose of 2.5 × 10^{19} 245-MeV ^{48}Ca ions was collected in this experiment. In one event (see Fig. 5) an ER with energy and TOF signal close to that expected for a Z=118 nucleus was followed by an 11.65-MeV α-particle absorbed by the focal-plane detector and a 10.71-MeV α-particle detected both by the focal-plane and side detectors, which was followed by SF. For the second event no signals were detected in the short ER-SF time interval. These events were observed at the instantaneous beam energy values of 245.6 MeV ($E^* = 29.8 \pm 2.0$ MeV) and 246.1 MeV ($E^* = 30.2 \pm 2.3$ MeV), respectively; which corresponds to the expected maximum for the 3n-evaporation channel, resulting in production of the even-even isotope ^{294}118. Moreover, the decay properties of descendant nuclei in the first decay chain are in agreement with ^{290}116 and ^{286}114 produced in the ^{245}Cm+^{48}Ca and ^{242}Pu+^{48}Ca reactions.

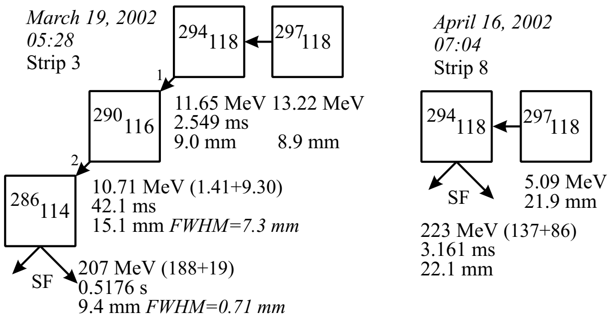

Fig. 5. Time sequences in the decay chains observed in the ^{249}Cf+^{48}Ca [16)]. FWHM position resolutions for escape α and SF with respect to ER are shown in italics.

The second decay chain does not reproduce the first one. The decay time $t_{SF} =$ 3.16 ms is quite close to the first α-decay time (2.55 ms) in the previous chain. One can propose that the observed SF with rather high deposited energy $E_{tot} = 223$ MeV (TKE∼245 MeV) is related also to fission of the ER ^{294}118 itself produced in the reaction ^{249}Cf(^{48}Ca,3n) with a cross section of about 0.7 pb.

In our previous experiments, the observed even-Z superheavy nuclei with Z=114, 116 and 118 underwent a few consecutive α-decays terminated by SF. For the neighboring odd-Z elements, especially their odd-odd isotopes, the probability of α-decay with respect to SF should increase due to hindrance for SF. For such odd-Z nuclei one might expect longer consecutive α-decay chains terminated by the SF of relatively light descendant nuclides ($Z \leq 105$). The decay pattern of these superheavy nuclei could provide valuable information about the influence of significant nuclear structure changes on the decay properties of these nuclei. In the course of decays, the increased stability of nuclei caused by the predicted *spherical* neutron shell N=184 (or perhaps N=172) should gradually become weaker for descendant isotopes. However, the stability of these nuclei at the end of the decay chains should increase again due to the influence of the *deformed* shell at N=162.

For these investigations, we chose the fusion-evaporation reaction ^{243}Am+^{48}Ca, leading to isotopes of element 115. According to calculations [10] based on the results of experiments on the synthesis of even-Z nuclei [5),8),11),15),16)], the 3n- and 4n-evaporation channels leading to isotopes ^{288}115 (N=173) and ^{287}115 (N=172) should be observed with the highest yields. The experiments were performed in July-August, 2003. Over this period, equal beam doses of 4.3×10^{18} ^{48}Ca projectiles were delivered to the target at two bombarding energies of 248 MeV ($E^* = 38.0 - 42.3$ MeV) and 253 MeV ($E^* = 42.4 - 46.5$ MeV) [17].

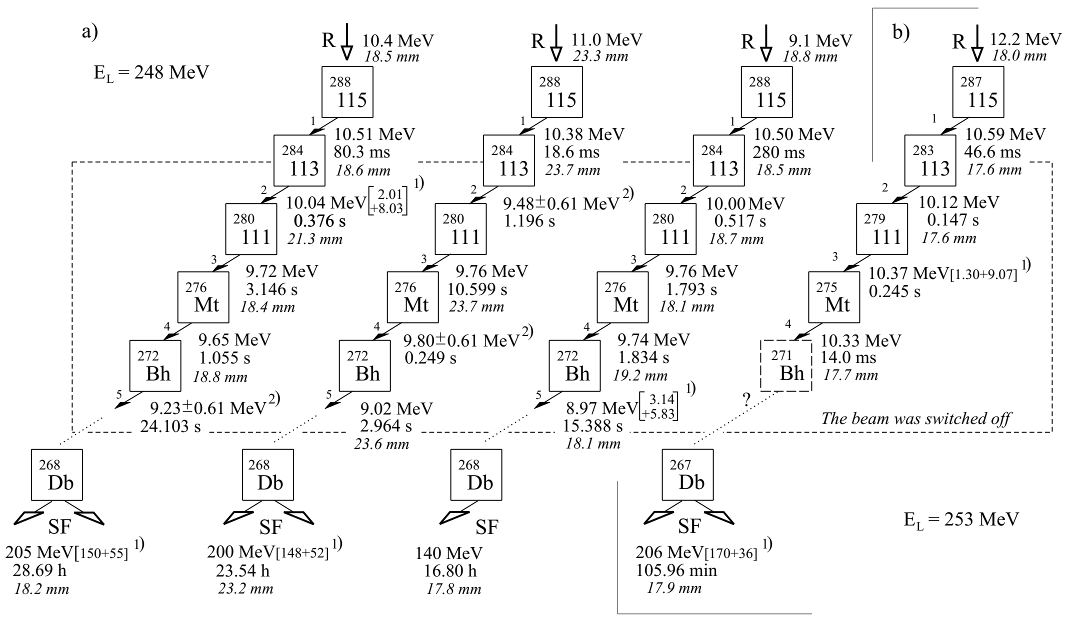

Fig. 6. Time sequences in the decay chains observed at $E_L = 248$ MeV (a) and $E_L = 253$ MeV (b) of ^{48}Ca bombarding ^{243}Am target. Measured energies, time intervals and vertical positions with respect to the top of the strips of the observed decay events are shown. 1) Energies of events detected by both the focal-plane and side detectors. 2) Energies of events detected by side detectors only. We have inserted an unobserved nuclide in the fourth decay chain.

The three similar decay chains observed at 248 MeV are shown in Fig. 6a. The implantations of recoils in the focal-plane detector were followed by α-particles with $E_\alpha = 10.46$ MeV. These sequences switched the ion beam off, and four more decays were detected in total time intervals of about 20 s in the absence of a beam-associated background. The last α-decay in the first chain and second and fourth α-decays in the second chain were registered by the side detectors only. However, with the actual α-counting rates, the probability that these α-particles appeared in the detector ($\Delta t \sim 30$ s) as random events can be estimated to be approximately 1.5%, so we assign them to the decay of the same implanted nuclei. The SF decay of the final nuclei in these chains was detected about one day after the last registered α decay.

At 253 MeV, the aforementioned ER-$\alpha_1 - ... - \alpha_5$-SF decay chains were not observed. However, a different decay chain, consisting of four decays and a spontaneous fission, was registered (Fig. 6b). The beam was switched off after the detection of an ER signal followed in 46.6 ms by an α particle with $E_\alpha = 10.59$ MeV. Three other decays were detected in a time interval of about 0.4 s in the absence of beam-associated background. After 106 minutes, the terminal SF event was detected in-beam. The radioactive properties of nuclei in this decay chain differ from those of the nuclei observed at the lower bombarding energy. The total decay time of this chain is about 10 times shorter and the α-decays are distinguished by higher α-particle energies and shorter lifetimes. Its production also required increasing the beam energy by about 5 MeV, so we assumed that the decay chain originates from another parent nucleus.

It is most reasonable that the different decay chains originate from neighboring parent isotopes of element 115, produced in the complete fusion reaction ^{243}Am+^{48}Ca followed by evaporation of three and four neutrons from the compound nucleus ^{291}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 resulted in reducing the ^{288}115-isotope yield and, at the same time, increasing the yield of the 4n-evaporation channel leading to the odd-even isotope ^{287}115. Corresponding cross sections for the 3n- and 4n-evaporation channels at the two projectile energies amount to $\sigma_{3n} = 2.7^{+4.8}_{-1.7}$ pb and $\sigma_{4n} = 0.9^{+3.2}_{-0.8}$ pb.

§3. Discussion

The α-particle spectra observed in these experiments from the decay of the nuclei with Z=112, 114 and 116 are characterized by well-defined transition energies. They follow the relationship between the probability and energy of α-decay (Viola-Seaborg formula) that was determined from even-even nuclei. This means that the observed transitions are as unhindered for the isotopes with odd mass numbers as they are for isotopes with even mass numbers.

The measured half-lives of odd-Z nuclei closely reproduce the values calculated from the measured α-decay energies for allowed transitions for the first two nuclei of the observed chains; thus the element 115 and element 113 isotopes have rather low hindrance factors, if any, for α-decay. For the isotopes of elements 111, Mt and Bh, the difference between measured and calculated T_α values results in hindrance factors of 3-10. These match the hindrance factors that can be extracted for the deformed odd-odd nucleus ^{272}111 and descendants produced in experiments at GSI[18] and

RIKEN [19]. One can suppose that in this region of nuclei, a noticeable transition from spherical to deformed shapes occurs at Z=109-111, resulting in the complication of the level structures of these nuclei. 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, see Fig. 7b. This assumption is in agreement with macroscopic-microscopic calculations [7]. The deformation parameter β_2 was calculated to be 0.072 and 0.138 for ^{288}115 and ^{284}113, respectively. As the decay chain recedes from the shell closure at Z=114, the deformation parameter β_2 increases to 0.200, 0.211 and 0.247 for ^{280}111, ^{276}Mt and ^{272}Bh, respectively.

The α-decay energies of the synthesized nuclei are given in Fig. 7 together with the available values of Q_α for the known isotopes with even Z≥100 and theoretical values [7]. Radioactive properties of isotopes with Z=112, 114, 116 and 118 are in qualitative agreement with the macro-microscopic model calculations that predict the nuclear shapes to be close to spherical in this domain.

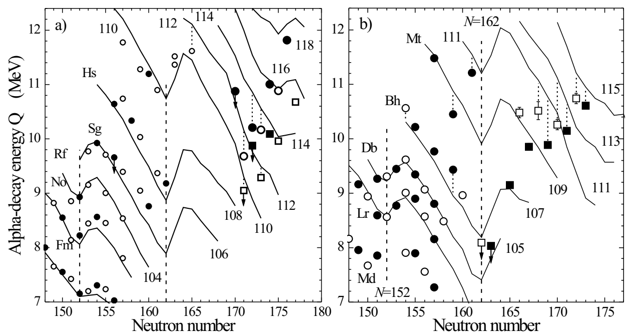

Fig. 7. Alpha-decay energy vs. neutron number for isotopes of even-Z (a) and odd-Z (b) elements with Z≥100 (solid symbols - even-N isotopes, open symbols - odd-N isotopes). Data at N≥171 (a) and N≥162 (b) are from [5, 8, 11, 15–17] and the present work. Solid lines show theoretical Q_α values [7].

The α-decay properties of the synthesized nuclei agree also with self-consistent calculations (see, e.g., [13, 20–22]). All the above theoretical approaches predict the existence of the "island of stability" in the region of superheavy elements. The principal result of the present work is the observation of the considerable increase in lifetimes of superheavy nuclei with $Z \geq 110$ with increasing neutron number. In this respect, the decay properties of the new nuclides observed in present experiments confirm theoretical expectations and can be considered proof of the existence of enhanced stability in the region of superheavy elements.

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References

1) Yu.A. Lazarev et al., Phys.Rev.Lett. **73**, 624 (1994); Phys.Rev.Lett. **75**, 1903 (1995); Phys.Rev. C **54**, 620 (1996).
2) A. Türler et al., Phys.Rev. C **57**, 1648 (1998); Ch.E. Düllmann et al., Nature **418**, 859 (2002).
3) Yu.Ts. Oganessian et al., Proceedings of the Fourth International Conference on Dynamical Aspects of Nuclear Fission, Casta-Papiernicka, Slovak Republic, 1998 (World Scientific, Singapore, 2000), p.334; K. Subotic et al., Nucl.Instr.Meth.Phys.Res. A **481**, 71 (2002).
4) Yu.Ts. Oganessian et al., Phys.Rev. C **64**, 054606 (2001).
5) Yu.Ts. Oganessian et al., Phys.Rev. C **62**, 041604(R) (2000); Phys.At.Nucl. **63**, 1679 (2000).
6) W.D. Myers and W.J. Swiatecki, Nucl.Phys. **A601**, 141 (1996).
7) R. Smolanczuk and A. Sobiczewski, in Proc. of XV Nuclear Physics Divisional Conference "Low Energy Nuclear Dynamics", St. Petersburg, Russia, 1995 (World Scientific, Singapore), p. 313; R. Smolanczuk, Phys.Rev. C **56**, 812 (1997); R. Smolanczuk, J. Skalski and A. Sobiczewski, Phys.Rev. C **52**, 1871 (1995); I. Muntian et al., Acta Phys.Pol. **B34**, 2073 (2003); Phys.At.Nucl. **66**, 1015 (2003).
8) Yu.Ts. Oganessian et al., Phys.Rev. C (2003), submitted.
9) R. Bass, in Proc. of the Symposium on Deep Inelastic and Fusion Reactions with Heavy Ions, West Berlin, 1979, edited by W. von Oertzen, Lecture Notes in Physics, Vol. 117 (Springer-Verlag, Berlin, 1980), p. 281.
10) V. Zagrebaev, in Proc. of the VIII International Conference on Nucleus-Nucleus Collisions (NN2003), Moscow, Russia, 2003, to be published.
11) Yu.Ts. Oganessian et al., Phys. Rev. C (2003), to be submitted.
12) Yu.Ts. Oganessian et al., Phys.Rev.Lett. **83**, 3154 (1999).
13) S. Ćwiok, W. Nazarewicz and P.H. Heenen, Phys.Rev.Lett. **83**, 1108 (1999).
14) Yu.Ts. Oganessian et al., Nature **400**, 242 (1999).
15) Yu.Ts. Oganessian et al., Phys.Rev. C **63**, 011301(R) (2001); Phys.At.Nucl. **64**, 1349 (2001); Eur.Phys.J. A **15**, 201 (2002).
16) Yu.Ts. Oganessian et al., JINR Communication D7-2002-287 (2002); Lawrence Livermore National Laboratory Report, UCRL-ID-151619 (2003).
17) Yu.Ts. Oganessian et al., Phys.Rev. C (2003), submitted.
18) S. Hofmann and G. Münzenberg, Rev.Mod.Phys. **72**, 733 (2000); S. Hofmann et al., Eur.Phys.J. A **14**, 147 (2002).
19) K. Morita, in Proc. of the VIII International Conference on Nucleus-Nucleus Collisions (NN2003), Moscow, Russia, 2003, to be published.
20) M. Bender, Phys.Rev. C **61**, 031302 (2000); P.-G. Reinhard et al., in Proc. Tours Symposium on Nuclear Physics IV, Tours, France, 2000 (AIP, New York, 2001), p.377.
21) S. Typel and B.A. Brown, Phys.Rev. C **67**, 034313 (2003).
22) Z. Ren, Phys.Rev. C **65**, 051304(R) (2002).