Possibilities for synthesis of new isotopes of superheavy elements in fusion reactions

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Background. In the "cold" fusion reactions based on the use of lead and bismuth targets, the proton-rich isotopes of superheavy (SH) elements up to $Z = 113$ have been produced. More neutron-rich isotopes of SH elements (up to $Z = 118$) have been synthesized in "hotter" fusion reactions of ^{48}Ca with actinide targets. α-decay half-lives of different isotopes of the same SH elements (for example, 112) were found to vary by several orders of magnitude. This indicates strong shell effects in this area of the nuclear map. The understanding of these effects and other properties of SH nuclei is strongly impeded by the absence of experimental data on decay properties of the not-yet-synthesized isotopes of SH elements located between those produced in the "cold" fusion reactions and those produced in the "hot" fusion reactions and also by the yet missing neutron-enriched isotopes of these elements.

Purpose. In this paper we search for the optimal fusion reactions which may be used to fill this gap of the nuclear map and significantly extend the area of known SH nuclei.

Method. For the calculation of the cross sections we use the same approach which was employed earlier for successful predictions of all ^{48}Ca induced fusion reactions.

Results. Several fusion reactions of the stable projectiles ^{40}Ar, ^{44}Ca, and ^{48}Ca with different isotopes of actinides (lighter and heavier than those that have been already utilized in the Dubna experiments) could be used for synthesis of new SH nuclei. Predicted cross sections for the production of new isotopes of SH nuclei were found to be quite large, and the corresponding experiments can be easily performed at existing facilities. For the first time a "narrow pathway" to the middle of the island of stability was found owing to possible β^+ decay of SH nuclei $^{291}115$ and $^{291}114$ which could be formed in ordinary fusion reactions.

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I. MOTIVATION

Significant progress has been achieved during the last 30 years in the synthesis of superheavy (SH) nuclei using the "cold" [1,2] and "hot" (^{48}Ca induced) [3] fusion reactions. The heaviest element, 118, was synthesized with the cross section of about 1 pb in the fusion of ^{48}Ca with the heaviest available target of ^{249}Cf [4]. A kind of "world record" of 0.03 pb in the production cross section of element 113 has been obtained in this field within more than half-year irradiation of a ^{209}Bi target with a ^{70}Zn beam [2]. Note that at the available experimental facilities several decay chains of evaporation residues (EvRs) can be detected within a few weeks of irradiation if the reaction cross section is about 1 pb. This remark is important for our final conclusions (see below).

Further progress in the synthesis of new elements with $Z > 118$ is not quite evident. Cross sections of the cold fusion reactions decrease very quickly with increasing charge of the projectile (they become less than 1 pb already for $Z \geqslant 112$ [1,2]). For the more asymmetric ^{48}Ca-induced fusion reactions, rather constant values (of a few picobarns) of the cross sections for the production of SH elements with $Z = 112$–118 have been predicted in Refs. [5,6]. This unusual (at first sight) behavior of the cross sections was explained in Refs. [5,6] by the relatively slow decrease of the fusion probability (in contrast to the more symmetric cold fusion reactions) and by the increasing survival probability of compound nuclei (CN) owing to increasing values of their fission barriers caused by the larger shell corrections as the CN approach the neutron and proton closed shells [7,8] in the region of the island of stability. These predictions have been fully confirmed by the experiments performed in Dubna [3] and later in Berkeley [9] and at GSI [10,11].

For the moment, $^{249}_{98}$Cf ($T_{1/2} = 351$ yr) is the heaviest available target that can be used in experiments. The half-life of the einsteinium isotope, $^{254}_{99}$Es, is 276 days, sufficient to be used as target material. In principle, this isotope might be produced in nuclear reactors, but it is rather difficult to accumulate the required amount of this matter (several milligrams) to prepare a target. We estimated the cross section for the production of element 119 in the hypothetical ^{48}Ca + ^{254}Es fusion reaction to be about 0.3 pb (see below), which is more promising than the ^{50}Ti + ^{249}Bk fusion reaction [12]. In any case, to get SH elements with $Z > 118$ in fusion reactions in a more realistic way, one should proceed to projectiles heavier than ^{48}Ca.

The strong dependence of the calculated EvR cross sections for the production of element 120 on the mass asymmetry in the entrance channel makes the projectile nearest to ^{48}Ca, ^{50}Ti, most promising for the further synthesis of SH nuclei. Our previous calculations demonstrated that the use of a titanium beam instead of ^{48}Ca decreases the yield of the same SH element owing to a worse fusion probability by about factor 20 [12] (e.g., if one compares the production of element 116 in the reactions ^{50}Ti + ^{244}Pu and ^{48}Ca + ^{245}Cm). Elements 119 and 120 can be produced in the fusion reactions of ^{50}Ti with ^{249}Bk and ^{249}Cf targets (or in the ^{54}Cr + ^{248}Cm fusion reaction) with the cross sections of about 0.04 pb [12], which are already at the limit of the experimental possibilities. The synthesis of these nuclei may encounter also another important

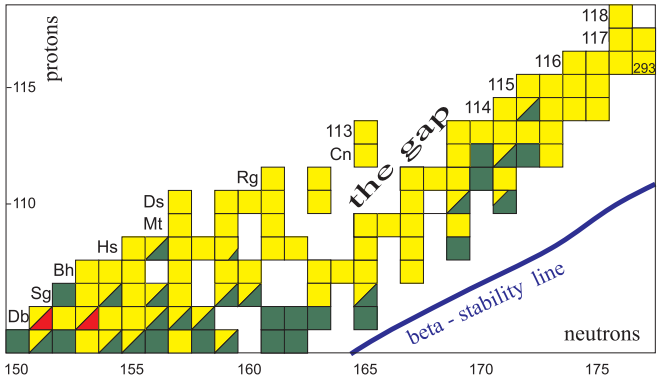

FIG. 1. (Color online) Known nuclei in the upper part of the nuclear map.

problem. The proton-rich isotopes of SH elements produced in these reactions are rather short-lived owing to large values of Q_α. Their half-lives are very close to the critical value of 1 μs needed for the CN to pass through the separator up to the focal-plane detector. The next elements (with $Z > 120$) being synthesized in such a way might already be beyond this natural time limit for their detection.

Thus, future studies of SH elements are obviously connected to the production of neutron-enriched and longer-lived isotopes of SH nuclei. The possibilities of using radioactive beams, multinucleon transfer reactions, and neutron capture processes for this purpose are discussed in Refs. [12–14].

At the same time, an important area of SH isotopes located between those produced in the cold and hot fusion reactions remains unstudied yet (see the gap in the upper part of the nuclear map in Fig. 1). Closeness of the island of stabillity (confirmed, for example, by the fact that the half-life of the isotope ^{285}Cn produced in the hot fusion reaction is longer by almost five orders of magnitude than the ^{277}Cn isotope of the same element produced in the cold synthesis) testifies about strong shell effects in this area of the nuclear map. Understanding these effects, as well as other properties of SH nuclei, is impeded significantly by the absence of experimental data on decay properties of the not-yet-synthesized isotopes of already-known SH elements. Knowledge of the trends (especially along the neutron axis) of all decay properties of these nuclei (fission, α- and β-decays) may help us to predict more accurately the properties of SH nuclei located at (and to the right of) the line of stability against β decay (the so-called "beta-stability line"), including those that are located in the island of stability.

An illustration of our prediction ability is demonstrated in Fig. 2, where the calculated half-lives are compared with the known experimental values for the isotopes of element 116. The half-lives of α decays were calculated with Q_α values taken from Refs. [7] and [8] using the Viola-Seaborg formula [15],

$$\log_{10} T_\alpha\,(\mathrm{s}) = \frac{aZ+b}{\sqrt{Q_\alpha\ (\mathrm{MeV})}} + cZ + d + h_{\log}, \qquad (1)$$

with the parameters obtained in Ref. [16]: $a = 1.661\,75$, $b = -8.5166$, $c = -0.202\,28$, $d = -33.9069$. The quantity $h_{\log}$ takes into account the hindrance of α decay for nuclei with

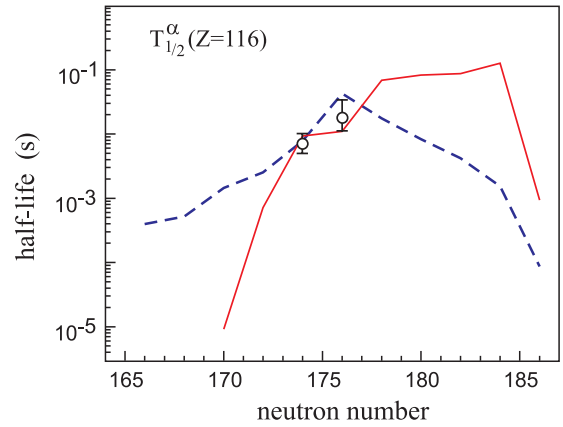

FIG. 2. (Color online) Half-lives of even-even isotopes of element 116 calculated with the Q_α values predicted in Ref. [7] (dashed line) and in Ref. [8] (solid line). Experimental data are taken from Ref. [17].

odd neutron and/or proton numbers [15]:

$$h_{\log} = \begin{cases} 0, & Z \text{ and } N \text{ are even,} \\ 0.772, & Z \text{ is odd and } N \text{ is even,} \\ 1.066, & Z \text{ is even and } N \text{ is odd,} \\ 1.114, & Z \text{ and } N \text{ are odd.} \end{cases} \qquad (2)$$

This formula gives quite perfect agreement with experimental half-lives for all nuclei with known values of Q_α.

As can be seen from Fig. 2, even the trends of dependence of the predicted half-lives on mass number are quite different in different models. Note that just the restricted number of experimental data in this region of the nuclear map hampers an appropriate adjustment of the parameters of different theoretical models to make the predictions closer and more realistic.

In this paper we study several fusion reactions leading to the formation of unknown isotopes of SH elements with masses "intermediate" between those already obtained in cold and hot fusion reactions. We calculated the excitation functions of the EvR cross sections for fusion reactions of stable nuclei ^{40}Ar, ^{44}Ca, and ^{48}Ca with different actinide targets (lighter and heavier than those that were used earlier in experiments with a ^{48}Ca beam). Most of the new SH nuclei produced in these reactions should experience α decay (with rather long decay chains). Besides other things, it allows one to apply cross-reactions to avoid a possible incorrect interpretation of the obtained experimental data in the case of a few detected events.

II. THE MODEL USED

The cross section of SH element production in a heavy-ion fusion reaction (with subsequent evaporation of x neutrons in the cooling process) is calculated as follows:

$$\sigma^{xn}_{\mathrm{EvR}}(E) = \frac{\pi}{k^2}\sum_{l=0}^{\infty}(2l+1)P_{\mathrm{cont}}(E,l)\cdot P_{\mathrm{CN}}(E^*,l)\cdot P_{xn}(E^*,l). \qquad (3)$$

The empirical channel coupling model [18] is used to calculate the penetrability of the multidimensional Coulomb

barrier $P_{\rm cont}(E,l)$ and the corresponding capture (sticking) cross section, $\sigma_{\rm cap}(E) = \pi/k^2 \sum(2l+1)P_{\rm cont}$. The adiabatic multidimensional potential energy surface itself is calculated within the extended version of the two-center shell model [19]. The standard statistical model [20] is used for the calculation of the survival probability $P_{xn}(E^*)$ of an excited CN. We use here the fission barriers and other properties of SH nuclei predicted by the macro-microscopic model [7]. Other parameters determining the decay widths and the algorithm itself for the calculation of the light particle evaporation cascade and γ emission can be found in Ref. [18]. Note that all the decay widths may be easily calculated by the Statistical Model Code of NRV allocated at the web site [21].

The calculation of the probability for the CN formation in competition with the quasifission process, $P_{\rm CN}(E^*,l)$, is the most difficult problem. In a well-studied case of near-barrier fusion of light and medium nuclei, when a fissility of CN is not so high, the fusing nuclei overcoming the potential barrier form a compound nucleus with a probability close to unity, that is, $P_{\rm CN} = 1$, and, thus, this reaction stage does not influence the yield of EvR at all. In the fusion of very heavy ions, the system of two touching nuclei may evolve with a high probability directly into the exit fission channels without CN formation, which means that the so-called process of "fast fission" or quasifission takes place [22].

At incident energies around the Coulomb barrier in the entrance channel the fusion probability $P_{\rm CN} \sim 10^{-3}$ for mass asymmetric reactions induced by ^{48}Ca and much less for more symmetric combinations used in the cold synthesis [5]. At near barrier collisions, the relative motion of heavy ions is very slow. In this case, much-faster-moving nucleons of colliding nuclei have enough time to adjust their motion over the volumes of two nuclei forming a two-center mononucleus; that is, the wave functions of valence nucleons follow the two-center molecular states spreading over both nuclei. Such behavior of nucleons is confirmed by explicit solution of the time-dependent Schröedinger equation [23] and by time-dependent Hartree-Fock calculations [24]. Subsequent evolution of the heavy two-center nuclear system is analyzed usually within stochastic equations of motion for collective degrees of freedom describing the transformation of the configuration of two touching nuclei into the configuration of more or less spherical CN (fusion) or into the configuration of two deformed reseparated fragments (dominating quasifission process) [25–31]. In all these approaches the elongation of the system (distance between nuclear centers) is the main collective degree of freedom. In some approaches it is the only one, whereas in others more variables (nucleon transfer, deformations, neck parameter) are also used.

The probability for the CN formation, $P_{\rm CN}(E^*,l)$, is found then as a simple diffusion process over the (parametrized) intrinsic barrier [28,29] (with advantage of analytical solution) or as a result of numerical solution of coupled stochastic equations describing a dissipative motion along the multidimensional potential energy surface (driving potential) calculated usually within the two-center shell model (adiabatic potential energy with the shell corrections).

Quite an opposite scenario of the CN formation is assumed in the "dinuclear system model" [32–34], in which a diabatic (repulsive at short distances) nucleus-nucleus potential energy is used. After stopping on the bottom of a potential pocket, two touching nuclei keep their relative distance and their "individuality." The nucleons of each nucleus move independently in the nonoverlapping mean fields (one-center states). The distance between two nuclei remains frozen (not included in equation of motion), and CN formation is assumed owing to nucleon transfer from a lighter nucleus to a heavier one.

In Ref. [25], the two-dimensional master equation was used for calculation of the probability for the CN formation, and a strong energy dependence of $P_{\rm CN}$ was found, which was confirmed recently in experiment [35]. Later, the multidimensional Langevin-type dynamical equations were proposed [30,36] for the calculation of $P_{\rm CN}$. The main idea is to study the evolution of the heavy nuclear system driven by the time-dependent multidimensional potential energy surface gradually transforming to the adiabatic potential calculated within the extended version of the two-center shell model [19]. In all, five collective degrees of freedom (distance between nuclear centers, deformations of the fragments, charge and mass asymmetry) are used in this approach to describe low-energy fusion-fission dynamics within the Langevin-type equation of motion. The same model is employed here for the calculation of the probability for CN formation, $P_{\rm CN}(E^*,l)$, in formula (3).

The actinide nuclei, used as targets in the fusion reactions studied below, are statically deformed, and the orientation effects play an important role in the fusion dynamics [30]. The fusion probability (formation of CN) is strongly suppressed for more elongated nose-to-nose initial orientations decaying mainly into the quasifission reaction channels. As a result, the preferable beam energies for the synthesis of SH elements in the fusion reactions with actinide targets are shifted to values that are several MeV higher than the corresponding Bass barriers [37] (calculated for spherical nuclei).

III. NEUTRON-ENRICHED SH NUCLEI AND THE NARROW PATHWAY TO THE ISLAND OF STABILITY

It is well known that there are no combinations of available projectiles and targets, the fusion of which may lead to SH nuclei located at the island of stability. Only the proton-rich isotopes of SH elements have been produced so far in fusion reactions (see Fig. 1). Radioactive ion beams may hardly solve this problem. Fusion cross sections for relatively light radioactive projectiles (such as ^{22}O, for example) are rather high and a beam intensity of about 10^8 pps is sufficient for synthesis of SH nuclei [12]. However the nuclei, being synthesized in such a way, would be also neutron deficient. For example, in the $^{22}\mathrm{O} + {}^{248}\mathrm{Cm}$ fusion reaction one may produce only already known neutron-deficient isotopes of rutherfordium, $^{265-267}$Rf.

In fusion reactions with heavier radioactive projectiles (such as ^{44}S, for example) new neutron-enriched isotopes of SH elements could be really produced, but in this case one needs to have a beam intensity of about 10^{12} pps to reach in experiment a 1 pb level of the corresponding EvR cross section [12], which is not realistic for the near future.

Still, several more neutron-rich actinide targets (^{250}Cm, ^{251}Cf, ^{254}Es) could be used, in principle, for production of SH nuclei shifted by one or two neutrons to the right side from those already synthesized in ^{48}Ca-induced fusion reactions (though they will be far from the beta-stability line, see Fig. 1). In Fig. 3 the EvR cross sections are shown for the synthesis of elements 116, 118, and 119 formed in fusion reactions of ^{48}Ca with ^{250}Cm, ^{251}Cf, and ^{254}Es targets. As mentioned above, the ^{254}Es target is rather exotic and hardly may be prepared, but a quite sufficient amount of the isotope ^{251}Cf ($T_{1/2} = 898$ yr)

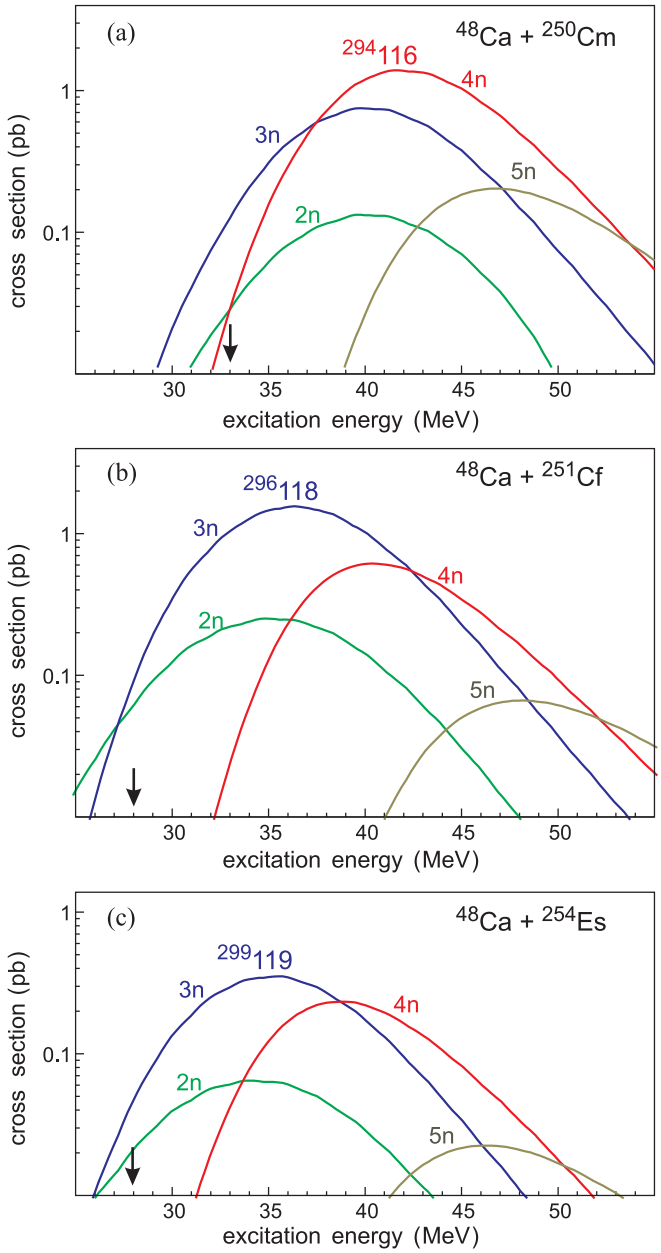

FIG. 3. (Color online) Production cross sections of elements 116 (a), 118 (b), and 119 (c) in the ^{48}Ca + ^{250}Cm, ^{48}Ca + ^{251}Cf, and ^{48}Ca + ^{254}Es fusion reactions. The numbers near the curves indicate the corresponding neutron evaporation channels. The arrows show positions of the corresponding Bass barriers.

is accumulated in nuclear reactors, and the only problem is its separation.

As can be seen, new neutron-rich isotopes of elements 116 (^{294,295}116) and 118 (^{295,296}118) may be synthesized in 3n and 4n evaporation channels of the ^{48}Ca + ^{250}Cm and ^{48}Ca + ^{251}Cf fusion reactions with the cross sections of about 1 pb. Subsequent α decays of the nuclei ^{295,296}118 pass through the known isotopes of elements 116, 114, and so on. It significantly facilitates their detection and identification. α-decay chains of ^{294}116 and ^{295}116 nuclei lead to absolutely new neutron-enriched isotopes of SH elements ended by the fission of seaborgium and/or rutherfordium isotopes located already at the stability line. The cross section for the production of element 119 in the ^{48}Ca + ^{254}Es fusion reaction is rather low (~0.3 pb), but still it is larger than the cross section of the ^{50}Ti + ^{249}Cf fusion reaction, which was estimated in Ref. [12] to be about 0.05 pb.

Another interesting feature of the fusion reactions ^{48}Ca + ^{250}Cm and ^{48}Ca + ^{254}Es (as well as the 2n evaporation channel of the reaction ^{48}Ca + ^{249}Bk) is an unexpected possibility to reach the middle of the island of stability just in fusion processes of "stable" nuclei. In these reactions relatively neutron-rich isotopes of SH elements 114 and 115 are formed as α-decay products of EvRs of the corresponding CN. These isotopes should have rather long half-lives and, thus, they could be located already in the "red" area of the nuclear map; that is, they may be β^+-decaying nuclei [38]. In Fig. 4 several possible decay chains of these isotopes are shown along with the corresponding values of Q_α and half-lives calculated with the use of nuclear masses predicted by Sobizcewski *et al.* [8] and by Möller *et al.* [7]. The SF half-lives are taken from Ref. [39] (with the hindrance factor 100 for odd nuclei), while the values in brackets are calculated by phenomenological relations [38] with the shell corrections taken from Ref. [7].

In accordance with our calculations of decay properties of SH nuclei [38], the isotopes ^{291}115 and ^{291}114 may experience not only α decay but also electron capture with a half-life of several seconds. If it is correct, the narrow pathway to the middle of the island of stability is suprisingly opened by production of these isotopes in subsequent α decays of elements 116, 117, and/or 119 produced in the ^{48}Ca + ^{250}Cm, ^{48}Ca + ^{249}Bk, and ^{48}Ca + ^{254}Es fusion reactions (see Fig. 4). The corresponding cross sections of these reactions are rather low; they are about 0.8 pb for the 3n evaporation channel of the ^{48}Ca + ^{250}Cm fusion reaction and 0.3 pb for the two last reactions (see Ref. [12] and bottom panel of Fig. 3). However, for the moment, this is the only method that is proposed for the production of SH nuclei located just in the middle of the island of stability. Further careful study of the decay properties of unknown SH nuclei located closer to the beta-stability line is needed to confirm the existence of such a possibility.

IV. HOW CAN THE GAP IN THE SUPERHEAVY MASS AREA BE CLOSED?

As mentioned above, understanding and predicting the properties of SH nuclei (including those located at the island of stability) are significantly impeded by fragmentary character

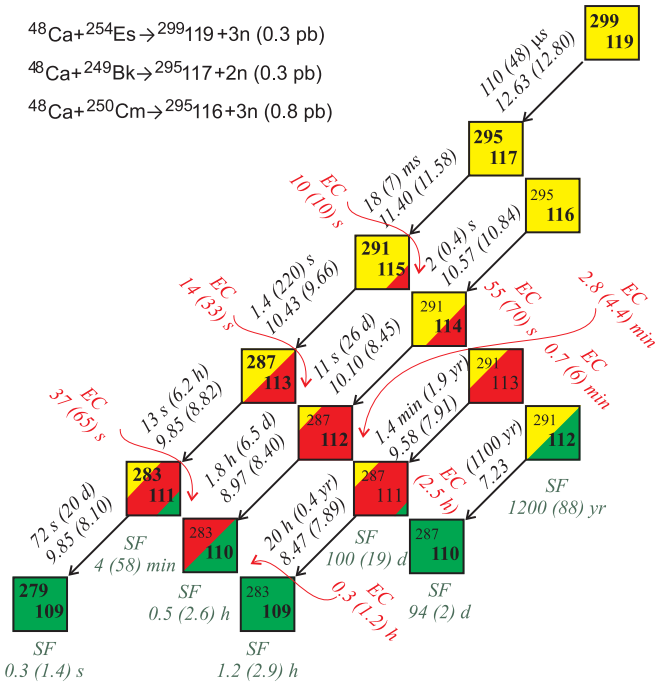

FIG. 4. (Color online) The pathway to the middle of the island of stability via a possible β^+ decay of the isotopes $^{291}115$ and $^{291}114$. The first isotope may be formed after α decay of $^{295}117$ ($2n$ evaporation channel of the $^{48}Ca + ^{249}Bk$ fusion reaction, cross section is 0.3 pb [12]) or after two α decays of $^{299}119$ ($3n$ evaporation channel of the $^{48}Ca + ^{254}Es$ fusion reaction). The second one, $^{291}114$, is formed after α decay of $^{295}116$ in the $3n$ evaporation channel of the $^{48}Ca + ^{250}Cm$ fusion reaction with cross section of about 0.8 pb. Decay half-lives and Q_α values (in MeV) are also shown calculated with nuclear masses of A. Sobizcewski *et al.* [8] and of P. Möller *et al.* [7] (in brackets).

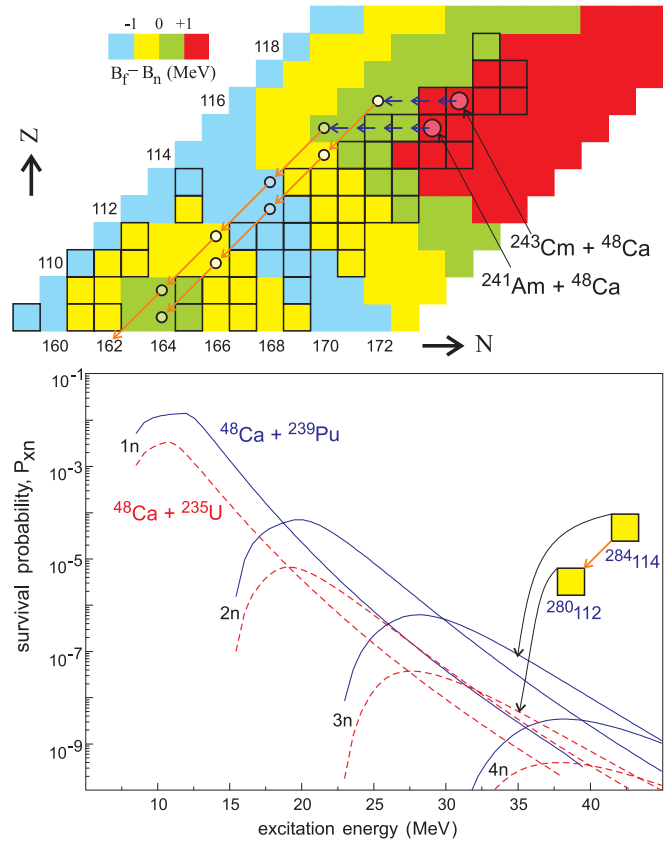

FIG. 5. (Color online) (Top) The values of $B_f - B_n$ as a function of proton and neutron numbers. Known isotopes of SH elements are marked by the bordered rectangles. As an example the CN $^{289}115$ and $^{291}116$, formed in fusion reactions $^{48}Ca + ^{241}Am$ and $^{48}Ca + ^{243}Cm$, are shown along with α-decay chains of their $4n$ and $3n$ EvRs, correspondingly. (Bottom) The survival probability of the CN $^{283}112$ and $^{287}114$ formed in the fusion reactions $^{48}Ca + ^{235}U$ (dashed curves) and $^{48}Ca + ^{239}Pu$ (solid curves) for the different neutron evaporation channels (CN angular momentum $l = 0$).

of experimental data. Only a few isotopes of SH elements with $Z \geqslant 112$ have been synthesized so far (see Fig. 1). This is explained, of course, by extremely low values of the corresponding production cross sections. However, recently, the synthesis of SH elements at the level of 1 pb became more or less a routine matter for several laboratories. The corresponding experiments require about 2-week irradiation time to detect several events (decay chains) of SH element formation. This means that many more unknown isotopes of SH elements could be synthesized now, and the gap between nuclei produced in the cold and hot fusion reactions could be closed at last.

Note that it can be done with the use of ordinary fusion reactions and, thus, with the use of existing recoil separators, in contrast with the mass-transfer reactions [13] for which separators of a new kind are needed. For this purpose several (rather cheap and available) isotopes of actinide elements can be used as the targets (for example, $^{233,235}U$, $^{239,240}Pu$, ^{241}Am, ^{243}Cm, and so on). Besides ^{48}Ca, the beams of ^{36}S, ^{44}Ca, and ^{40}Ar are also of interest. Here we analyze several most promising fusion reactions leading to the synthesis of new isotopes of SH elements located to the left (neutron poor) side from those already synthesized in ^{48}Ca-induced fusion reactions (see Fig. 1).

First of all, we found that it is more convenient (and easier) to close the gap "from above" by the synthesis of new isotopes of SH elements with larger values of Z, their subsequent α-decay chains just fill the gap. This unexpected finding is simply explained by greater values of survival probabilities of the corresponding nuclei with $Z = 115, 116$ as compared to those with $Z = 111, 112$. In the top panel of Fig. 5 the values of $B_f - B_n$ are shown for the SH mass area, where B_f is the fission barrier and B_n is the neutron separation energy (an odd-even effect is smoothed here). As can be seen, the values of $B_f - B_n$ are much higher, for CN with $Z \sim 116$ as compared with CN of 112 element formed in fusion reactions of ^{48}Ca with neutron-deficient isotope of uranium. As a result, the corresponding survival probability of lighter CN is smaller by more than one order of magnitude.

As an example, the bottom panel of Fig. 5 shows survival probabilities of two CN, $^{283}112$ and $^{287}114$, formed in the fusion reactions $^{48}Ca + ^{235}U$ and $^{48}Ca + ^{239}Pu$. The excitation energies of both CN (at collision energies equal to the corresponding Bass barriers, 195 and 198 MeV,

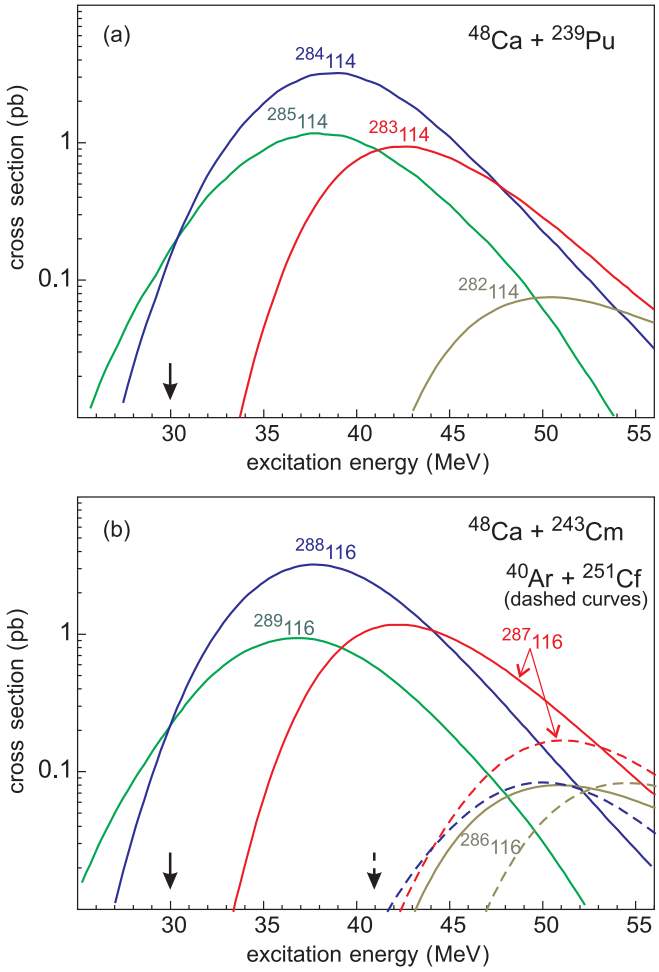

FIG. 6. (Color online) Production cross sections for the new isotopes of elements 114 (a) and 116 (b) in the ^{48}Ca + ^{239}Pu, ^{48}Ca + ^{243}Cm, and ^{40}Ar + ^{251}Cf (dashed curves) fusion reactions. The arrows show positions of the corresponding Bass barriers.

correspondingly) are just the same for two reactions (they are about 30 MeV).

In spite of the decrease of the fusion probability with increasing charge number of the target nucleus, we may conclude that the EvR cross sections for the ^{48}Ca + ^{239}Pu reaction should be higher (by about one order of magnitude for the 3n evaporation channel) owing to the larger survival probability of ^{287}114 compound nucleus as compared to ^{283}112. Numerical calculations fully confirm this conclusion. This means that the new isotopes of element 112 (at least, ^{280,279}112) could be easier synthesized and studied as α-decay products of the heavier elements, 114 and/or 116.

In Fig. 6 the calculated EvR cross sections are shown for the production of new isotopes of elements 114 and 116 in the fusion reactions of ^{48}Ca with ^{239}Pu and ^{243}Cm targets and for the ^{40}Ar + ^{251}Cf fusion reaction leading to the same CN as in the ^{48}Ca + ^{243}Cm reaction. A high intensive beam of ^{40}Ar can be obtained quite easily. This material is also much cheaper than ^{48}Ca. However, as can be seen from Fig. 6, the use of an ^{40}Ar beam is less favorable than ^{48}Ca. This is attributable to the much "hotter" character of the ^{40}Ar + ^{251}Cf fusion reaction

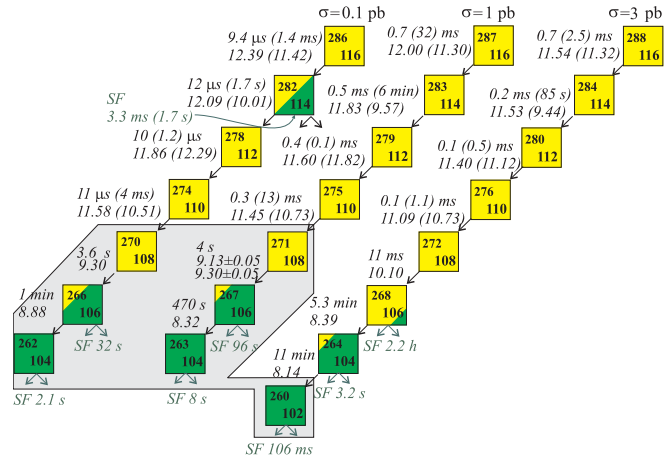

FIG. 7. (Color online) Possible decay chains of the new isotopes $^{286–288}$116 formed in the ^{48}Ca + ^{243}Cm fusion reaction. Decay half-lives and Q_α values (in MeV) are calculated with nuclear masses of A. Sobizcewski *et al.* [8] and of P. Möller *et al.* [7] (in brackets). The decay properties of the isotopes ^{271}108,^{267}106, and ^{263}104 are taken from Ref. [40]. For the isotopes ^{272}108,^{268}106, and ^{264}104 of the third chain the extrapolated experimental masses from Ref. [41] were used to calculate their decay properties. The decay properties of nuclei located in the shaded area are known.

(only the cross sections for the 5n evaporation channels are comparable for both reactions).

More than ten new isotopes of even elements from Z = 104 to 116 could be produced in the ^{48}Ca + ^{239}Pu and/or ^{48}Ca + ^{243}Cm fusion reactions, which just fill the gap in the superheavy mass area. The production cross sections are high enough to perform such experiments at available facilities. All the decay chains, most probably, reach finally known nuclei. This fact significantly facilitates the identification of the new SH isotopes. Three possible decay chains of the unknown isotopes of element 116 produced in the 3n, 4n, and 5n evaporation channels of the ^{48}Ca + ^{243}Cm fusion reaction are shown in Fig. 7.

We found that the ^{48}Ca + ^{241}Am fusion reaction is the best for the production of the new isotopes of odd SH elements filling the gap. The production cross sections for the new isotopes $^{284–286}$115 in this reaction are about 0.1 pb, 2 pb, and 4 pb, respectively, that is, high enough to be measured. The corresponding excitation functions are shown in the top panel of Fig. 8. In the bottom panel of this figure a possible decay chain of the isotope ^{285}115 is shown, which ends by spontaneous fission of the known lawrencium isotope, ^{261}103. Owing to possible β^+ decay of the nuclei ^{265}105 and ^{269}107, this chain may "jump" to the known rutherfordium and seaborgium isotopes, ^{265}104 and ^{269}106, reported to be produced in Ref. [9] as decay products of SH nucleus ^{285}114 (5n evaporation channel of the ^{48}Ca + ^{242}Pu fusion reaction).

The more neutron-deficient isotopes of element 115 could be produced in the ^{44}Ca + ^{243}Am fusion reaction (note that ^{44}Ca is a more abundant and available material as compared to ^{48}Ca). However, in this reaction the excitation energy of the formed CN is 10 MeV higher than in the ^{48}Ca + ^{241}Am fusion reaction. As a result, the corresponding excitation functions

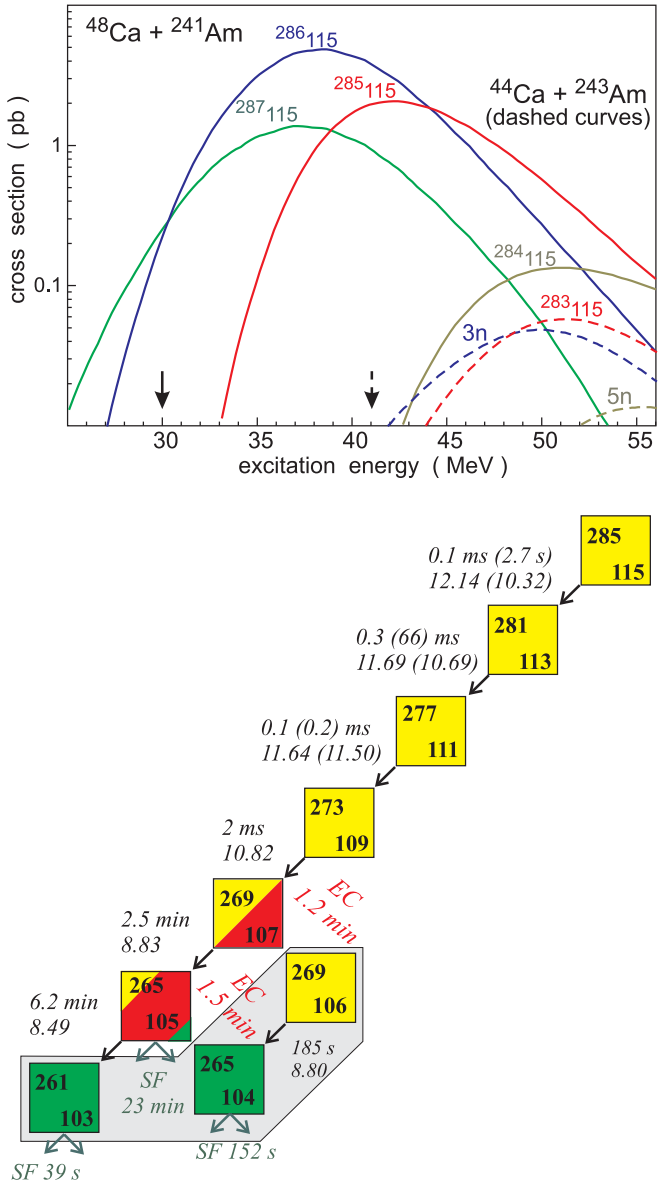

FIG. 8. (Color online) (Top) Production cross sections for new isotopes of element 115 in the fusion reactions ^{48}Ca + ^{241}Am and ^{44}Ca + ^{243}Am (3n, 4n, and 5n evaporation channels, respectively, dashed curves). The arrows show positions of the corresponding Bass barriers. (Bottom) Possible decay chain of the isotope ^{285}115 formed in the 4n evaporation channel of the ^{48}Ca + ^{241}Am fusion reactions. The decay half-lives and Q_α values (in MeV) are also shown. They are calculated with nuclear masses of Sobizcewski *et al.* [8] and of Möller *et al.* [7] (in brackets). For the isotopes of elements 103 and 105 the extrapolated experimental masses from Ref. [41] have been used. The decay properties of the isotopes ^{265}104 and ^{269}106 are taken from Ref. [9]. ^{261}103 is a known nucleus.

(see the dashed curves in the upper panel of Fig. 8) are shifted to higher energies at which the survival probability of the CN is much lower. Thus, we may conclude again that the ^{48}Ca beam is preferable also for the production of neutron-deficient SH nuclei in fusion reactions with lighter isotopes of actinide targets as compared to the use of $^{42–44}$Ca beams and heavier actinide targets.

V. SUMMARY

One might think that the epoch of ^{48}Ca in the production of SH nuclei was finished by the synthesis of element 118 in the ^{48}Ca + ^{249}Cf fusion reaction [4]. However, this projectile still could be successfully used for the production of new isotopes of SH elements.

The extension of the area of known isotopes of SH elements is extremely important for better understanding of their properties and for developing the models which will be able to predict well the properties of SH nuclei located beyond this area (including those at the island of stability). We found that the ordinary fusion reactions could be used for the production of new isotopes of SH elements. The gap of unknown SH nuclei, located between the isotopes which were produced earlier in the cold and hot fusion reactions, could be filled in fusion reactions of ^{48}Ca with available lighter isotopes of Pu, Am, and Cm. The same nuclei can be produced, in principle, with the use of lighter projectiles ^{40}Ar and/or ^{44}Ca and heavier actinide targets, but the corresponding EvR cross sections of such reactions were found to be lower than with ^{48}Ca-induced fusion reactions (owing to higher excitation energy of the CN formed in reactions with weaker bound ^{40}Ar and/or ^{44}Ca nuclei).

The neutron-enriched isotopes of SH elements may be also produced with the use of a ^{48}Ca beam if a ^{250}Cm target would be prepared. In this case we get a real chance to reach the island of stability owing to a possible β^+ decay of ^{291}114 and ^{287}112 nuclei formed in the 3n evaporation channel of this reaction with a cross section of about 0.8 pb. The same path to the island of stability is opened also in the 2n evaporation channel of the ^{48}Ca + ^{249}Bk fusion reaction ($\sigma^{2n}_{\rm EvR} \sim 0.3$ pb) leading to the isotope ^{291}115 having a chance for β^+ decay.

Note finally that all the proposed fusion reactions (having rather large EvR cross sections at the level of 1 pb) can be performed at existing experimental facilities in contrast with the widely discussed multinucleon transfer reactions which require design and construction of new experimental setups.

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