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Production of heavy and superheavy neutron-rich nuclei in neutron capture processes

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The neutron capture process is considered as an alternative method for production of superheavy (SH) nuclei. Strong neutron fluxes might be provided by nuclear reactors and nuclear explosions in the laboratory frame and by supernova explosions in nature. All these cases are discussed in the paper. There are two gaps of short-lived nuclei (one is the well-known fermium gap and the other one is located in the region of $Z = 106$–108 and $N \sim 170$) which impede the formation of SH nuclei by rather weak neutron fluxes realized at available nuclear reactors. We find that in the course of multiple (rather "soft") nuclear explosions these gaps may be easily bypassed, and thus, a measurable amount of the neutron-rich long-living SH nuclei located at the island of stability may be synthesized. Existing pulsed reactors do not allow one to bypass these gaps. We formulate requirements for the pulsed reactors of the next generation that could be used for production of long-living SH nuclei. Natural formation of SH nuclei (in supernova explosions) is also discussed. The yield of SH nuclei relative to lead is estimated to be about 10^{-12}, which is not beyond the experimental sensitivity for a search of SH elements in cosmic rays.

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I. MOTIVATION

The continent of stable elements stretches up to the lead-bismuth cape stipulated by the crossing of the closed neutron ($N = 126$) and proton ($Z = 82$) shells. These shells lead to a sharp increase in α-decay Q values for elements with $Z > 82$ and to the appearance of an area of unstable nuclei with $82 < Z < 90$ separating the continent from the first "thorium-uranium" island of stability (the heaviest elements found in nature). The subsequent regions of stability of superheavy (SH) nuclei were predicted to originate by the next neutron and proton closed shells at $Z \sim 114$ and $Z \sim 164$ [1] (of course, these magic numbers depend on the underlying nuclear shell models).

Many attempts to find more or less stable SH elements in nature have not yet succeeded [2]. "Cold" fusion reactions based on the closed-shell target nuclei of lead and bismuth (which initially looked very promising) lead to the production of proton-rich isotopes of SH elements with very short half-lives located far from the β-stability line [3,4]. Many years ago it was proposed to produce the most neutron-rich isotopes of SH elements in fusion of ^{48}Ca with available actinide targets, ^{244}Pu, ^{248}Cm, and others (see, e.g., Ref. [5]). This possibility has only recently been realized. The isotope of element 112, ^{285}Cn, observed in the decay chains of SH nuclei ^{289}114 and ^{293}116 produced in the 3n evaporation channels of ^{48}Ca + ^{244}Pu [6] and ^{48}Ca + ^{248}Cm [7] fusion reactions, reveals the very long half-life of about 30 s. This is 5 orders of magnitude longer compared with the half-life of the more neutron-deficient isotope ^{277}Cn produced in a "cold" fusion reaction [3]. This fact evidently confirms the existence of an island of stability. However, one needs to add six to eight more neutrons to reach the most stable SH nuclei of this island (see below), which is impossible in any fusion reactions of stable beams with available targets.

At any rate, the 10-year epoch of ^{48}Ca irradiation of actinide targets for synthesis of SH elements is over. The heaviest available target, californium ($Z = 98$), had been used to produce element 118 [8]. Note that the more or less constant values (of a few picobarns) predicted earlier of the cross sections for the production of SH elements with $Z = 112 \div 118$ in ^{48}Ca-induced fusion reactions [9,10] (caused by a gradual increase in the fission barriers of the compound nuclei formed in these reactions) have been fully confirmed by experiments performed in Dubna and later in Berkeley [11] and at the GSI [12].

To get SH elements with $Z > 118$ in fusion reactions, one should proceed to projectiles heavier than ^{48}Ca. The strong dependence of the calculated evaporation residue (EvR) cross sections for the production of element 120 on the mass asymmetry in the entrance channel makes the projectile closest to ^{48}Ca, i.e., ^{50}Ti, most promising for further synthesis of SH nuclei [13]. Use of a titanium beam instead of ^{48}Ca decreases the yield of SH nuclei (by a factor of 20 on average), mainly due to the lower fusion probability. The estimated EvR cross sections for the 119 and 120 SH elements synthesized in ^{50}Ti-induced fusion reactions [13] ($\sim$0.05 pb) are quite reachable in available experimental setups, though they require a much longer time of irradiation than for ^{48}Ca fusion reactions.

The yield of SH nuclei (number of events per day) depends not only on the cross section but also on the beam intensity and target thickness. In this connection, other projectile-target combinations should also be considered. Most neutron-rich isotopes of element 120 may be synthesized in the three fusion reactions ^{54}Cr + ^{248}Cm, ^{58}Fe + ^{244}Pu, and ^{64}Ni + ^{238}U, leading to the same SH nucleus, ^{302}120. These three

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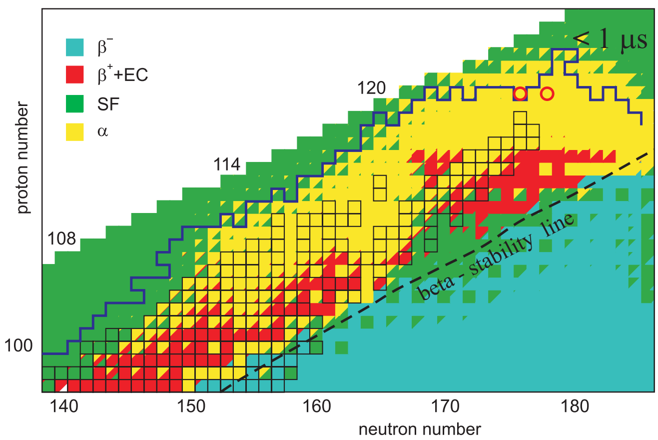

FIG. 1. (Color online) Calculated preferable decay modes of nuclei in the upper part of the nuclear map [14]. Known nuclei are denoted by rectangles. The solid line shows the border of short-living nuclei, with half-lives of <1 μm. The two circles mark the locations of the isotopes that could be synthesized in fusion reactions of ^{50}Ti + ^{249}Cf ($3n$ evaporation channel) and ^{54}Cr + ^{248}Cm ($4n$ evaporation channel).

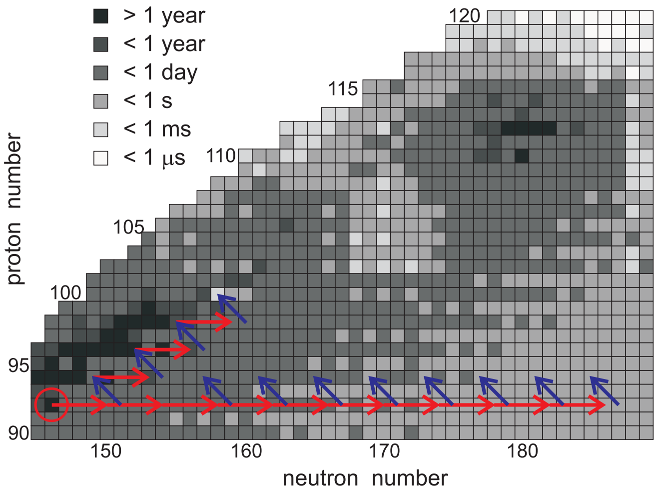

FIG. 2. (Color online) Half-lives of nuclei in the upper part of the nuclear map. Schematic views of slow (terminated at the short-living fission fermium isotopes) and fast neutron capture processes with subsequent β^- decays are shown by arrows.

combinations are not of equal value. The estimated EvR cross sections for the more symmetric ^{58}Fe + ^{244}Pu and ^{64}Ni + ^{238}U reactions are lower than those for the less symmetric ^{54}Cr + ^{248}Cm combination [13], which, in its turn, is quite comparable with the Ti-induced fusion reaction (still there is an advantage factor of 2 or 3 for ^{50}Ti + ^{249}Bk and ^{50}Ti + ^{249}Cf fusion cross sections compared with ^{54}Cr + ^{248}Cm). All these reactions must be considered quite promising for synthesis of the new elements 119 and 120. The final choice between them depends not as much on the difference in the cross sections as on other experimental conditions (availability of appropriate targets, beam intensities, etc.).

As already mentioned, due to the bending of the stability line toward the neutron axis, in fusion reactions of stable nuclei one may produce only proton-rich isotopes of heavy elements. The half-lives of the isotopes of element 120 synthesized in titanium- and/or chromium-induced fusion reactions are very close to the critical value of 1 μm needed to pass through the separator up to the focal plane detector. The next elements ($Z > 120$) synthesized in this way might be beyond this natural limit for their detection (see Fig. 1). Thus, future studies of SH elements are obviously connected with the production of neutron-enriched longer living isotopes of SH nuclei.

Note that for elements with $Z > 100$, only neutron-deficient isotopes (located to the left of the stability line) have been synthesized so far (see Fig. 1), while the unexplored area of heavy neutron-rich nuclides (located on the stability line and to the right of it) is extremely important for nuclear astrophysics investigations and, in particular, for the understanding of the r process of astrophysical nucleogenesis (a sequence of neutron capture and β-decay processes). Fusion reactions of stable nuclei do not allow one to explore this area. The use of beams of radioactive nuclei will hardly solve this problem owing to their low intensities [13].

Multinucleon transfer processes in low-energy collisions of actinide nuclei (like U + Cm) may really lead to the formation of neutron-rich long-living isotopes of SH elements. Shell effects (antisymmetrizing quasifission process with the preferable formation of nuclei close to a doubly magic lead isotope) might significantly enhance the corresponding cross sections [13,15]. Despite the difficulties of separation of the transfer reaction products, experiments of this kind are planned in the very near future, to obtain new neutron-rich nuclei not only in the SH mass area but also for $Z \sim 70 \div 90$ [16,17] (important for the astrophysical r-process area around the last waiting point, $N \sim 126$). However, the predicted cross sections for production of heavy neutron-rich nuclei in multinucleon transfer reactions become lower than 1 pb for SH elements with $Z > 107$ [18].

The neutron capture process is an alternative (oldest and natural) method for the production of new heavy elements. Strong neutron fluxes might be provided by nuclear reactors and nuclear explosions under laboratory conditions and by supernova explosions in nature. It is well known that the "fermium gap," consisting of the short-living fermium isotopes $^{258-260}$Fm located on the β stability line and having very short half-lives for spontaneous fission, impedes the formation of nuclei with $Z > 100$ by the weak neutron fluxes realized in existing nuclear reactors. In nuclear and supernova explosions (fast neutron capture) this gap may be bypassed, if the total neutron fluence is high enough. Theoretical models also predict another region of short-living nuclei located at $Z = 106 \div 108$ and $A \sim 270$ (see Fig. 2).

In this paper we study the possibility of synthesizing heavy elements in multiple "soft" nuclear explosions and in pulsed reactors. We find that in the first case these two gaps may be easily bypassed, and thus, a measurable amount of the neutron-rich long-living SH nuclei of the island of stability may be synthesized. In the second case we formulate requirements for pulsed reactors of the next generation, which eventually could be used for the production of long-living SH nuclei. Finally, we use our model to perform a simple estimation of the possibility of natural formation of SH nuclei in the astrophysical r process.

II. NUCLEOSYNTHESIS BY NEUTRON CAPTURE

The synthesis of heavier nuclei in the reaction of neutron capture with subsequent β^- decay is a well-studied process (see, e.g., Refs. [5], [19], and [20]). Relative yields of the isotopes formed in this process may be found as a solution of the following set of differential equations (somewhat simplified here):

$$\begin{aligned}\frac{dN_{Z,A}}{dt} &= N_{Z,A-1}n_0\sigma_{n\gamma}^{Z,A-1} - N_{Z,A}n_0\sigma_{n\gamma}^{Z,A}\\ &\quad - N_{Z,A}\left[\lambda_{Z,A}^{\beta-} + \lambda_{Z,A}^{\text{fis}} + \lambda_{Z,A}^{\alpha}\right]\\ &\quad + N_{Z-1,A}\lambda_{Z-1,A}^{\beta-} + N_{Z+2,A+4}\lambda_{Z+2,A+4}^{\alpha}, \qquad (1)\end{aligned}$$

where n_0 is the neutron flux (number of neutrons per square centimeter per second) and $\lambda_{Z,A}^{i} = \ln 2/T_{1/2}^{i}$ is the decay rate of the nucleus (Z, A) into channel i (i.e., β^- and α decays and fission). For simplicity, here we ignore the energy distribution of the neutrons and, thus, the energy dependence of the neutron capture cross section $\sigma_{n\gamma}^{Z,A}$. Neutrons generated by fission in nuclear reactors and in explosions are rather fast (far from the resonance region). In the interval of 0.1–1 MeV the neutron capture cross section is a smooth function of energy with a value of about 1 b, which is used below for numerical estimations. Note that integration over the neutron energy may be performed very easily and does not change the conclusions obtained. The simplest version of the reaction chain, where only the neutron capture reactions are retained [first line in Eq. (1)], was considered recently in Ref. [21].

A. Decay properties of heavy-neutron-rich nuclei

To solve Eq. (1) numerically, one needs to know the decay properties of neutron-rich nuclei, which have not yet been studied experimentally. This is a key problem, which significantly complicates any analysis of multiple-neutron capture processes. Theoretical estimations of half-lives for α decay are rather reliable because they depend only on ground-state masses, which are very close in different theoretical models. Here we use the ground-state masses obtained by Möller *et al.* [22]. This model (the droplet model for the macroscopic part and the folded Yukawa mean-field potential for the shell correction calculation) is one of the most known and tested. For the half-lives of α decays we used the well-known Viola-Seaborg formula [23] with the coefficients proposed by Sobiczewski *et al.* [24],

$$\log_{10} T_{1/2}^{\alpha}(\text{s}) = \frac{aZ + b}{\sqrt{Q_\alpha(\text{MeV})}} + cZ + d + h_{\log}, \qquad (2)$$

where $a = 1.661\,75$, $b = -8.5166$, $c = -0.202\,28$, $d = -33.9069$ [24], and $h_{\log}$ takes into account hindrance of α decay for nuclei with odd neutron and/or proton numbers [23]:

$$h_{\log} = \begin{cases} 0, & Z \text{ and } N \text{ are even;}\\ 0.772, & Z \text{ is odd and } N \text{ is even;}\\ 1.066, & Z \text{ is even and } N \text{ is odd;}\\ 1.114, & Z \text{ and } N \text{ are odd.}\end{cases} \qquad (3)$$

Note that the phenomenological calculation of $T_{1/2}^{\alpha}$ is the most justified and accurate at the moment. The other universal decay laws for α decay may be found in the literature (see, e.g., Refs. [25] and [26]). However, the error arising from uncertainty in Q_α is much larger than the one owing to the inaccuracy of the phenomenological Viola-Seaborg formula. Heavy-ion (cluster) radioactivity of SH nuclei is also possible [27], but its probability is much lower compared with α decay and we ignore it here.

Half-lives of allowed β decays also depend on the ground-state masses of the nuclei and may be estimated by the empirical formula [28]

$$\log_{10}\left[f_0 T_{1/2}^{\beta}(\text{s})\right] = 5.7 \pm 1, \qquad (4)$$

where the Fermi function f_0 is calculated by the standard formulas (see, e.g., Ref. [29]). The assumption about allowed transitions for β^- decays of unknown heavy-neutron-rich nuclei (which are of interest here) is quite reasonable owing to the large Q values of these decays: in the daughter nucleus a level may be found that is close to the ground state and which fulfils the conditions of allowed β decay. In Eq. (4) we use the constant value 4.7, which was found to be more appropriate for heavy nuclei. Details of the calculations of the Fermi function and comparison with available experimental β-decay half-lives (which demonstrates better agreement with increasing Q values) can be found in Ref. [14].

The fission half-lives are the most uncertain quantities in Eqs. (1) because fission is a very complicated process. Reliable analysis of the fission process requires knowledge of the multidimensional potential energy surface as well as of the collective inertia parameters. The most realistic calculations of the fission half-lives are based on a search for the least active path in a multidimensional deformation space. Such calculations can be performed only for a specific nucleus or in a restricted area of the nuclear map. We used the ground-state masses and shell corrections for heavy and SH nuclei proposed by Möller *et al.* [22] and then we applied the empirical formula for the estimation of fission half-lives. For this purpose, we employed the relation of Swiatecki [30] based on the idea of a dominant role of the fission barrier in the fission probability:

$$\begin{aligned}\log_{10} T_{1/2}^{\text{fis}}(\text{s}) &= 1146.44 - 75.3153Z^2/A\\ &\quad + 1.637\,92(Z^2/A)^2 - 0.011\,982\,7(Z^2/A)^3\\ &\quad + B_f(7.236\,13 - 0.094\,702\,2Z^2/A)\\ &\quad + \begin{cases} 0, & Z \text{ and } N \text{ are even;}\\ 1.538\,97, & A \text{ is odd;}\\ 0.808\,22, & Z \text{ and } N \text{ are odd.}\end{cases} \qquad (5)\end{aligned}$$

Here $B_f = B_f^{\text{LDM}} + \delta U_{\text{g.s.}}$ is the fission barrier, which was calculated as a sum of the liquid-drop barrier and the ground-state shell correction. The coefficients of the systematics, Eq. (5), were determined by a fitting to the experimental data and to the rather realistic theoretical predictions [31,32] for the region of $100 \leqslant Z \leqslant 120$ and $140 \leqslant N \leqslant 190$.

More details about our calculations of decay properties of heavy nuclei can be found in Ref. [14]. They are also shown schematically in Figs. 1 and 2. In calculations of multiple-neutron capture (see below), the theoretical values of $T_{1/2}^{\alpha}$, $T_{1/2}^{\beta}$ and/or $T_{1/2}^{fis}$ were replaced by experimental ones, if known. In accordance with our predictions, the most stable SH nuclei located at the island of stability are the β-stable isotopes of copernicium ($Z = 112$)with neutron numbers $N = 179$ and $N = 181$ and with the half-lives of about 100 years (note that in the literature different doubly magic spherical nuclei are predicted, depending on the parametrization [33]). At any rate, as mentioned above, to produce these nuclei in a multiple-neutron capture process, one needs to bypass the two areas of short-living fissile nuclei, namely, the fermium gap ($Z = 100$) and the region of $Z = 106 \div 108$ and $A \sim 270$.

B. Multiple nuclear explosions

To test our model we first described available data on the fast neutron capture process realized in nuclear explosions. In this case the time of neutron capture, $\tau_n = (n_0\sigma_{n\gamma})^{-1} \sim 1\ \mu\text{s} \ll T_{1/2}(Z, A)$, is much shorter than the half-lives of the produced nuclei (up to the neutron drip line). Keeping only the first two terms on the right-hand side of Eq. (1), we get the following analytical solution [with initial conditions $N_{Z,A}(t = 0) = 1$ and $N_{Z,A+k}(t = 0) = 0$ at $k > 0$, where k is the number of captured neutrons]:

$$N_{Z,A+k} = \frac{x^k}{k!}e^{-x}. \tag{6}$$

This relation can be used to understand the fast neutron capture process and for a preliminary estimation of relative yields of heavy nuclei synthesized in such a process. Here $x = n\sigma_{n\gamma}$, $n = n_0\tau$ is the total neutron fluence (neutrons per square centimeter), and τ is the duration of explosive neutron irradiation. Thus, the dimensionless quantity $x = n\sigma_{n\gamma}$ is an average number of captured neutrons. It is the key factor characterizing the neutron capture process. In nuclear explosions the neutron fluence reaches the values of $10^{25}\ \text{cm}^{-2}$, so that $x \sim 1$ and more than 10 neutrons could be captured during one exposure with a duration of about 1 μs [5].

In Fig. 3 the experimental data on the yield of transuranium nuclei in the test thermonuclear explosion "Mike" [34] are compared with those calculated by Eqs. (1) assuming a 1-μs neutron exposure of 1.3×10^{24} neutrons/cm^2 with a subsequent 1-month decay time. Note that elements 99 and 100 (einsteinium and fermium) were first discovered in debris from the Mike explosion. As shown, in this case the fermium gap does not influence the yields of nuclei with $Z > 100$, which roughly relation (6).

The resulting charge number of the synthesized nuclei might be increased by sequential neutron flux exposure if two or several nuclear explosions were generated in close proximity to each other. This natural idea was discussed many years ago [35]. At that time the experts (such as Edward Teller) concluded that technically it could be realized. The possibility of using laser-energized fusion pellets for multiple-neutron-capture nucleosynthesis was also discussed [36]. Note that at that time some doubts about the possibility of production of SH nuclei either in the astrophysical r-process or in man-made nuclear explosions were expressed in Ref. [37] based on the new calculation of fission barriers and neutron separation energies for neutron-rich heavy nuclei. However, no quantitative estimations have been done for the yields of SH-neutron-rich nuclei in such processes.

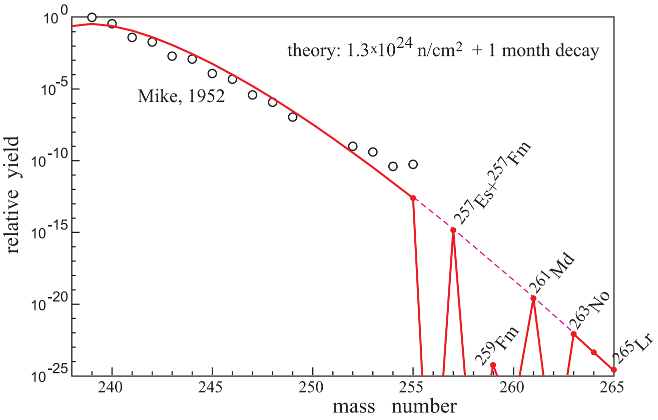

FIG. 3. (Color online) Experimental (open circles) and calculated relative yields of heavy nuclei in the test nuclear explosion "Mike" [34].

Here we apply our model to estimate the enhancement of the production of SH nuclei located at the island of stability in a process of multiple-neutron irradiation of a uranium target by subsequent (rather "soft") nuclear explosions. This process is illustrated in the upper part of Fig. 4. In the bottom part of this figure the probabilities of heavy-element formation are shown for 1, 3, and 10 subsequent short-time (1-μs) neutron exposures of 10^{24} neutrons/cm^2, following each other within a time interval of 10 s, with a final 1-month waiting time (needed to reduce the strong radioactivity of the material produced and to perform some experimental measurements).

We found that the result depends both on the neutron fluence $n = n_0\tau$ and on the time interval between two exposures. The neutron fluence should be high enough to shift the produced neutron-rich isotopes to the right from the second gap of unstable fissile nuclei located at $Z = 106 \div 108$ and $A \sim 270$ (see Figs. 1 and 2). The dependence on the time interval between two exposures is not as crucial. The result almost does not depend on this parameter if time interval is longer than several milliseconds (to avoid approaching the neutron drip line after several exposures) and shorter than a few minutes (to avoid β^- decay of the nuclei produced in the area of fission instability; $Z = 106 \div 108$ and $A \sim 270$).

Our results demonstrate for the first time that multiple rather "soft" nuclear explosions could really be used for the production of a noticeable (macroscopic) amount of neutron-rich long-lived SH nuclei. Leaving aside any discussion of the possibility of such processes and associated technical problems, we want to emphasize the sharp increase in the probability of formation of heavy elements with $Z \geqslant 110$ in multiple-neutron irradiations: enhancement by several tens of orders of magnitude (see Fig. 4). This probability is high enough for some SH elements (see the region above the dotted line in Fig. 4) to perform their experimental identification.

C. Pulsed nuclear reactors

It is also interesting to study the same process of multiple-neutron exposures realized in pulsed nuclear reactors. Here the pulse duration can be much longer than in nuclear explosions

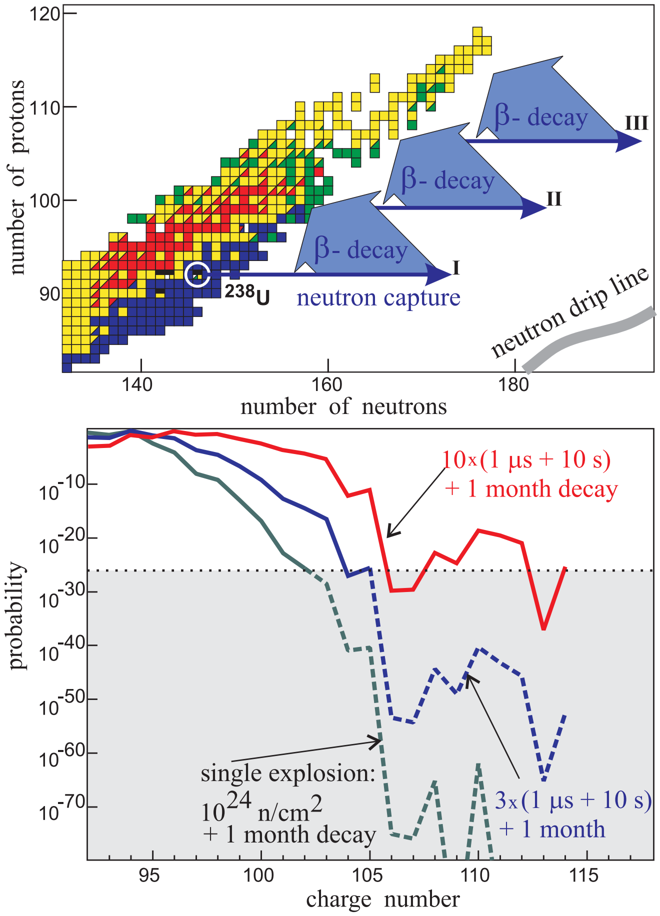

FIG. 4. (Color online) Schematic of multiple-neutron irradiation of initial ^{238}U material (top) and probability of formation of heavy nuclei (bottom) in such processes (1, 3, and 10 subsequent explosions). The dotted line denotes the level of few atoms.

(up to a few milliseconds). However, the neutron fluence usually does not exceed 10^{16} neutrons/cm^2 in existing nuclear reactors ($n_0 \sim 10^{19}$ neutrons/cm^2 s during a 1-ms pulse). Thus, the quantity $x = n\sigma_{n\gamma}$ is about 10^{-8}, the time of neutron capture $\tau_n = (n_0\sigma_{n\gamma})^{-1} \sim 10^5$ s, and only the nearest long-lived isotopes ($A + 1$ or $A + 2$) of irradiated elements can be formed during the pulse; see formula (6). Multipulse irradiation here corresponds, in fact, to a "slow" neutron capture process, in which new elements with larger charge numbers are situated close to the line of stability and finally reach the fermium gap, where the process stops (see Fig. 2). The result of numerical solution of Eq. (1) for the neutron capture process in an ordinary pulsed reactor is shown in Fig. 5 by the dashed line. In this case, the probability of formation of heavy elements with $Z > 100$ is negligibly small, independent of the number of pulses and total time of irradiation.

The situation might change if one were able to increase the intensity of the pulsed reactor somehow. The neutron fluence in one pulse and the frequency of pulses should be high enough to bypass both gaps of short-lived nuclei on the way to the island of stability (see Fig. 2). Thus, the specification of high-intensity pulsed reactors of the next generation depends strongly on the properties of heavy-neutron-rich nuclei located to the right of these gaps. These nuclei have not been discovered yet (see Fig. 1), and undoubtedly, certain experimental efforts should be made to resolve this problem.

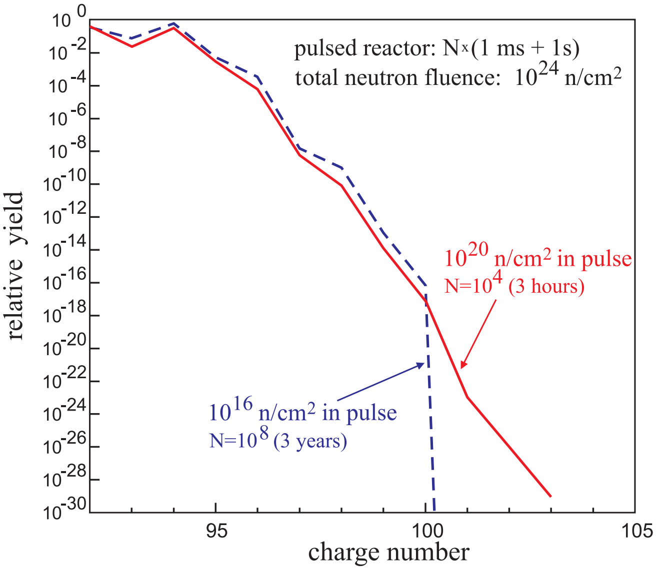

FIG. 5. (Color online) Relative yields of heavy elements in an ordinary pulsed reactor (10^8 pulses of 10^{16} neutrons/cm^2 neutron fluence each; dashed line) and in a high-intensity pulsed reactor (10^4 pulses of 10^{20} neutrons/cm^2 neutron fluence each; solid line). Total neutron fluence is 10^{24} neutrons/cm^2 for both cases.

Using our theoretical estimations for the decay properties of these nuclei (see above), we have found that an increase of the neutron fluence in an individual pulse by about 3 orders of magnitude compared with existing pulsed reactors, i.e., up to 10^{20} neutrons/cm^2, could be quite sufficient to bypass both gaps (see the solid curve in Fig. 5).

D. Formation of SH nuclei in astrophysical *r* processes

The astrophysical *r* process of nucleosynthesis is usually discussed to explain the observed abundance of heavy elements in the universe. In this process some amount of SH elements of the island of stability might also be produced if the fast neutron flux is sufficient to bypass the two gaps of fission instability mentioned above. Strong neutron fluxes are expected to be generated by neutrino-driven proto-neutron-star winds that follow core-collapse supernova explosions [38] or by the mergers of neutron stars [39]. Estimation of relative yields of SH elements is a difficult problem that depends both on the features of neutron fluxes and on the experimentally unknown decay properties of heavy-neutron-rich nuclei. We mention only one of a very few such calculations made recently [40], which gives the ratio of the yields of SH elements and uranium $\mathrm{Y(SH)/Y(U)} = 10^{-2}$–$10^{-20}$.

Here we make a very simple estimation of the possibility of formation of SH nuclei during the astrophysical *r* process of neutron capture. This estimation is based on the following assumptions. (i) SH nuclei are relatively short-lived [14]. They are absent in stars initially, while the distribution of other elements is rather close to their abundance in the universe.

(ii) SH nuclei may appear (and survive) in the last (rather cold) stage of the astrophysical r process when the observed abundance of heavy elements (in particular, thorium- and uranium-to-lead ratios) is also reproduced. (iii) An existing (experimental) abundance of stable nuclei may be used as an initial condition. During intensive neutron irradiation, initial thorium and uranium materials are depleted, transforming into heavier elements and going to fission, while more abundant lead and lighter stable elements enrich thorium and uranium. (iv) Unknown total neutron fluence may be adjusted in such a way that the ratios Y(Th)/Y(Pb) and Y(U)/Y(Pb) maintain their experimental values at the end of the process. Simultaneously, for a given neutron fluence, one gets the relative yield of SH elements, Y(SH)/Y(Pb) (in accordance with our estimation, ^{291}Cn and ^{293}Cn are the most stable SH nuclei [14]; their half-lives are about 100 years).

We performed calculations, similar to those described above, starting from initial relative abundances of heavy elements corresponding to experimental values (see, e.g., Ref. [41]). The value of the neutron flux n_0 was fixed at 10^{24} cm^{-2} s^{-1} and the total neutron fluence $n = n_0\tau$ was regulated by the time of exposure τ. Note that at such a high neutron flux the final result depends only on the total neutron fluence (not on n_0 and τ separately). After neutron irradiation a waiting time of 100 years was applied to obtain the final distribution of nuclei after all the decays. This time is still shorter than the half-lives of some α-decayed plutonium, curium, and californium isotopes, and we added their yields to the yields of their daughter thorium and uranium products. For the calculations we used only half of the nuclear map (from medium to SH masses) and found that the results obtained do not depend on the choice of the low border of the (Z,n) net used if it is below lead by about 60 mass units (i.e., we start the calculations from the Xe-Ba region of the nuclear map and ignore the contribution coming from lighter nuclei).

The results of our calculations are presented in Fig. 6, where the yields relative to lead of thorium, uranium, and long-living SH copernicium isotopes are shown, depending on the total neutron fluence. At low neutron fluxes the initial thorium and uranium nuclei increase their masses and charges (after neutron capture and subsequent β^- decay), find themselves in a region of fission instability, and drop out. Thus, their numbers decrease relative to lead, which, in contrast to Th and U, has an additional feed from lighter nuclei. Some increase in uranium material at very low neutron fluences (see Fig. 6) is due to the contribution from thorium. Note that a relatively low neutron fluence may lead to some excess of uranium over thorium, Y(U) > Y(Th). The contribution from lead to thorium and uranium becomes noticeable only when the probability of capture of 24 neutrons is not negligible. At a neutron fluence $n \sim 1.5 \times 10^{25}$ cm^{-2} (=15 neutrons/b), burning of thorium and uranium is compensated by the increasing contribution from lighter stable nuclei with $Z \leqslant 83$. However, at this neutron fluence the final abundance of thorium and uranium is still too low, and only at $n \sim 2 \times 10^{25}$ cm^{-2} are both ratios, Y(Th)/Y(Pb) and Y(U)/Y(Pb), close to the observed values.

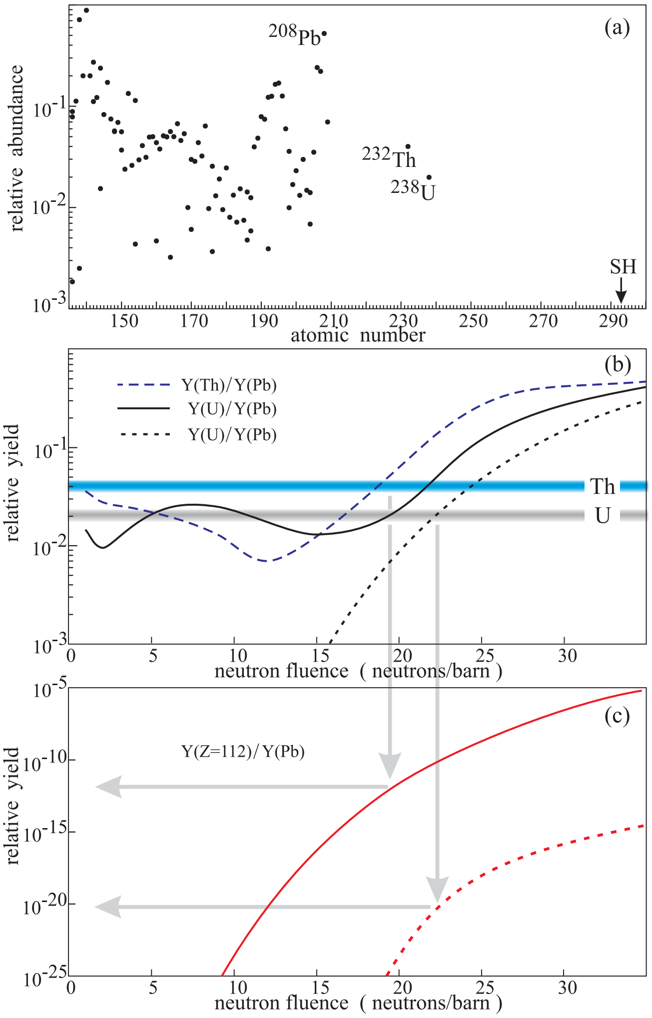

FIG. 6. (Color online) (a) Initial abundance relative to lead of nuclei [41]. The position of rather stable SH copernicium isotopes is indicated by the arrow. (b) Yields relative to lead of thorium (dashed curve) and uranium (solid curve) nuclei depending on the total neutron fluence in the astrophysical r process. Horizontal bars show experimental values of thorium and uranium abundances relative to lead. (c) The same for the relative yield of long-living SH copernicium isotopes ^{291}Cn and ^{293}Cn ($Z = 112$). Dashed curves in (b) and (c) show the yields of uranium and SH elements in the case of a zero initial abundance of thorium and uranium at the beginning of the r process (see text).

From the bottom panel in Fig. 6 one can see that, at this neutron fluence, the yield relative to lead of most stable isotopes of SH element 112, namely, ^{291}Cn and ^{293}Cn, is about 10^{-12}, which is not extremely low and provides hope of finding them in nature (probably in cosmic rays). This result does not depend strongly on the unknown half-lives of these SH nuclei (if they are comparable to or longer than several tens of years). However, the result depends on decay properties of heavy nuclei with $Z > 100$ located at (and to the right of) the β stability line (see Figs. 1 and 2). Note, also, that the ratio Y(SH)/Y(Pb) strongly depends on the neutron fluence, which cannot be explicitly determined yet from the ratios Y(Th)/Y(Pb) and Y(U)/Y(Pb). It is clear that the ratio Y(SH)/Y(Pb) will be higher if (in contrast to our estimations [14]) the most stable SH nuclei are the neutron-rich isotopes of hassium ($Z = 110$), and Y(SH)/Y(Pb) is lower for the production of SH elements with $Z > 112$.

We also checked a somewhat different scenario of SH element formation allowing that, in contrast to assumption iii (see above), initial thorium and uranium nuclei are completely burned in the s process of neutron capture before supernova explosion (note that in the s process, SH elements cannot be formed). In this case we started from zero initial abundance of these elements and fitted the neutron fluence during the r process in such a way that the ratios Y(Th)/Y(Pb) and Y(U)/Y(Pb) reach their experimental values at the end of this process. As before, the neutron fluence found determines unambiguously the ratio Y(SH)/Y(Pb). For this scenario we got the yield of SH nuclei, which is lower by 8 orders of magnitude than in the first case (see dashed curves in Fig. 6).

III. SUMMARY

We have shown for the first time that a macroscopic amount of long-living SH nuclei located at the island of stability might really be produced in multiple (rather "soft") nuclear explosions, if such processes could be realized technically. This goal could also be reached by using the pulsed nuclear reactors of the next generation, if their neutron fluence per pulse is increased by about 3 orders of magnitude. Our estimation of the possibility of production of SH elements in the astrophysical r process (namely, the neutron-rich copernicium isotopes ^{291}Cn and ^{293}Cn, with half-lives longer than several tens of years) is not very explicit but also not completely pessimistic: their yield relative to lead could be about 10^{-12} if we assume initial natural abundance of all the elements (including thorium and uranium) at the beginning of the astrophysical r process. This ratio is not beyond the experimental sensitivity for a search for SH elements in nature [2,42]. The question is, How long are their half-lives? In accordance with our estimations [14], the half-lives of most long-living copernicium isotopes, ^{291}Cn and ^{293}Cn, do not exceed several hundred years. At any rate, even this short time provides hope of finding relatively long-living SH nuclei in cosmic rays. The result turns out to be more pessimistic (i.e., lower by 8 orders of magnitude) if the initial thorium and uranium nuclei are completely burned in the s process of neutron capture before supernova explosion. Note that experimental study of the decay properties of heavy nuclei located along the β stability line (and to the right of it; see Fig. 1) is extremely important for a more accurate analysis of the neutron capture processes (including astrophysical ones) in the upper part of the nuclear map.

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