Superheavies: Short-Term Experiments and Far-Reaching Designs

V. I. Zagrebaev, A. V. Karpov, I. N. Mishustin and Walter Greiner

Abstract Low values of the fusion cross sections and very short half-lives of nuclei with $Z > 120$ put obstacles in synthesis of new elements. However the fusion reactions of medium mass projectiles with different actinide targets still can be used for the production of the not-yet-synthesized SH nuclei. 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. Cross sections for the production of these nuclei are predicted to be rather large, and the corresponding experiments can be easily performed at existing facilities. The use of heavier actinide targets give us a chance to produce more neutron enriched SH isotopes. Moreover, for the first time, a narrow pathway is found to the middle of the island of stability owing to possible β^+ decay of SH isotopes which can be formed in ordinary fusion reactions of stable nuclei. Multi-nucleon transfer processes at near barrier collisions of heavy (and very heavy, U-like) ions seem to be quite realistic reaction mechanism allowing us to produce new neutron enriched heavy nuclei located in the unexplored upper part of the nuclear map. Neutron capture reactions can be also used for the production of the long-living neutron rich SH nuclei. Strong neutron fluxes might be provided by pulsed nuclear reactors and by nuclear explosions in laboratory conditions and by supernova explosions in nature. All these possibilities are discussed in the chapter.

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W. Greiner (ed.), *Exciting Interdisciplinary Physics*,
FIAS Interdisciplinary Science Series, DOI: 10.1007/978-3-319-00047-3_5,

1 Motivation

It is well known that the last element whose lifetime is comparable to the age of earth and that occurs in macroscopic quantities in nature is uranium. All the other elements with $Z > 92$ have been produced in laboratory experiments (see historical review [1]). The progress in this field is quite impressive—26 handmade new heavy elements have been synthesized within 60 years. Some transuranium elements (up to californium) are produced in considerable quantity (by neutron capture process accompanied with β^--decay in nuclear reactors) sufficient to prepare a target which can be used for synthesis of the next superheavy (SH) elements in fusion reactions.

However the transuranium elements become more and more unstable as they get bigger. In the late sixties, the dream of the rather stable SH elements arose. Theoretical nuclear physicists around S. G. Nilsson (Lund) [2, 3] and from the Frankfurt school [4, 5] predicted that so-called closed proton and neutron shells should counteract the repelling Coulomb forces. Atomic nuclei with special "magic" proton and neutron numbers and their neighbours could again be rather stable.

Many attempts to find more or less stable SH elements in nature were not succeeded yet [6]. The "cold" fusion reactions based on the closed shell target nuclei of lead and bismuth (which looked initially very promising) lead to the production of proton rich isotopes of SH elements with very short half-lives located far from the beta-stability line [7, 8]. 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 [9]. Such a possibility has been realized only recently. 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 the ^{48}Ca+^{244}Pu [10] and ^{48}Ca+^{248}Cm [11] fusion reactions, reveals very long half-life of about 30 s. This is five orders of magnitude longer as compared with the half-life of more neutron deficient isotope ^{277}Cn produced in the "cold" fusion reaction [7]. This fact evidently confirms an existence of the island of stability! However one needs to add 6–8 neutrons more to reach the most stable SH nuclei of this island, which is impossible in any fusion reactions of stable beams with available targets.

Anyhow, a ten years epoch of ^{48}Ca irradiation of actinide targets for the synthesis of SH elements is over. The heaviest available target of californium ($Z = 98$) had been used to produce the element 118 [12]. Note, that earlier predicted more or less constant value (of a few picobarns) of the cross sections for the production of SH elements with $Z = 112 \div 118$ in ^{48}Ca induced fusion reactions [13, 14] (caused by the gradual increase of the fission barriers of the compound nuclei formed in these reactions) have been fully confirmed by the experiments performed in Dubna and later in Berkeley [15] and GSI [16, 17].

To get SH elements with $Z > 118$ in fusion reactions, one should proceed to heavier than ^{48}Ca projectiles. 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 nearest to ^{48}Ca projectile, ^{50}Ti, most promising for further synthesis of SH nuclei [18]. The use of the titanium beam instead of ^{48}Ca

decreases the yield of SH nuclei (by factor 20 on average) mainly due to a worse fusion probability. The estimated EvR cross sections for the 119 and 120 SH elements synthesized in the ^{50}Ti induced fusion reactions [18] ($\sim$ 0.05 pb) are quite reachable at available experimental setups, though one needs much longer time of irradiation than for the ^{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 be also considered. Most neutron-rich isotopes of element 120 may be synthesized in the ^{54}Cr+^{248}Cm fusion reactions.

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. 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. Still the estimated cross section for the production of element 119 in the hypothetical ^{48}Ca+^{254}Es fusion reaction is about 0.3 pb, which is more promising as compared with the ^{50}Ti+^{249}Bk fusion reaction. The calculated excitation functions for the synthesis of SH elements 119 and 120 in the fusion reactions of ^{48}Ca, ^{50}Ti and ^{54}Cr with actinide targets are shown in Fig. 1. The experiments with titanium and chromium beams aimed on the production of SH elements 119 and 120 are currently in progress at GSI.

The synthesis of these nuclei may encounter also another important 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 be already beyond this natural time limit for their detection.

Thus, future studies of SH elements are obviously connected with the production of neutron enriched and longer living isotopes of SH nuclei. The possibilities of using radioactive beams, multi-nucleon transfer reactions and neutron capture processes for this purpose are discussed in Refs. [18–20]. At the same time an important area of SH isotopes located between those produced in the cold and hot fusion reactions remains

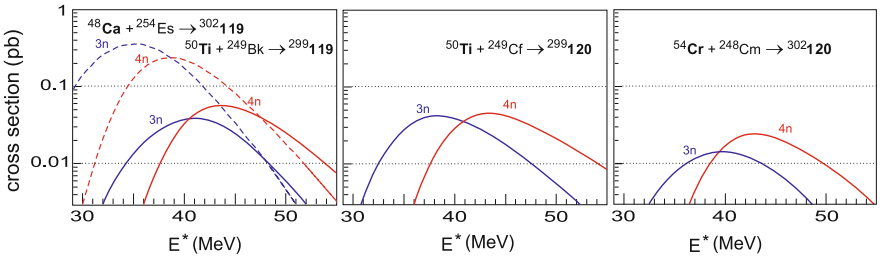

Fig. 1 Excitation functions for the production of SH elements 119 and 120 in the 3n and 4n evaporation channels of the ^{48}Ca+^{254}Es (*dashed curves*), ^{50}Ti+^{249}Bk, ^{50}Ti+^{249}Cf and ^{54}Cr+^{248}Cm (*solid curves*) fusion reactions

unstudied yet. Approaching the island of stability (see above) 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 or fragmentary character of experimental data on decay properties of the not-yet-synthesized isotopes of already known SH elements.

2 How can the Gap in Superheavy Mass Area be Filled?

As can be seen from Fig. 2, there is an important area of SH isotopes located between those produced in the cold and hot fusion reactions remains unstudied yet. This is explained 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 at 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 (see below) 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. We found that it is more convenient (and easier) to fill the gap "from above" by synthesis of new isotopes of SH elements with larger values of Z, their subsequent α decay chains just fill the gap [21]. This unexpected finding is simply explained by greater values of survival probabilities

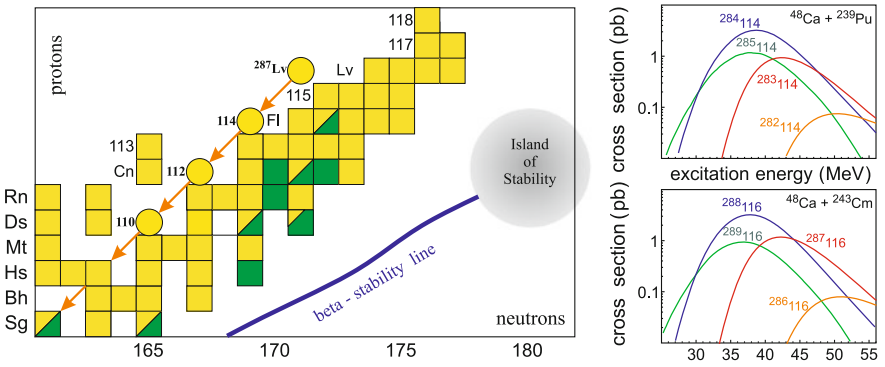

Fig. 2 Filling the gap in SH mass area. Production cross sections for the new isotopes of elements 114 (Fl) and 116 (Lv) in the ^{48}Ca+^{239}Pu and ^{48}Ca+^{243}Cm fusion reactions. Decay chain of the isotope ^{287}Lv (4n channel of the ^{48}Ca+^{243}Cm fusion reaction) is shown on the *left panel*

of the corresponding nuclei with $Z = 115, 116$ as compared to those with $Z = 111, 112$. The values of $B_f - B_n$ are much higher for compound nuclei with $Z \sim 116$ as compared with compound nuclei 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.

In Fig. 2 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. 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 reach finally known nuclei. This fact significantly facilitates the identification of the new SH isotopes. Note, that high intensive beam of ^{40}Ar could be also used. This material is much cheaper than ^{48}Ca. However we found that the use of an ^{40}Ar beam is less favorable as compared with ^{48}Ca [21]. This is attributable to the much "hotter" character of the ^{40}Ar+^{251}Cf fusion reaction. As a result, the corresponding excitation functions for this reaction are shifted to higher energies, and the cross sections are lower by one order of magnitude.

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, i.e. high enough to be measured. The more neutron deficient isotopes of element 115 could be produced in the ^{44}Ca+^{243}Am fusion reaction (^{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 are shifted to higher energies at which the survival probability of the CN is much lower. Thus, 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.

3 The Narrow Pathway to the Island of Stability

It is well known that there are no combinations of available projectiles and targets, 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. 2). Radioactive ion beams hardly may solve this problem. Fusion cross sections for relatively light radioactive projectiles (like ^{22}O, for example) are rather high and beam intensity of about 10^8 pps is sufficient for synthesis of SH nuclei [18]. However the nuclei, being synthesized in such a way, would be also neutron deficient. For example, in the ^{22}O+^{248}Cm fusion reaction one may produce only already known neutron deficient isotopes of rutherfordium, $^{265-267}$Rf. In fusion reactions with heavier radioactive projectiles (like ^{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 [18], which is not realistic for the nearest 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. 2). 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 cross sections of about 1 pb [21].

More 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 evaporation residues 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, i.e., they may be β^+-decaying nuclei [22]. In Fig. 3 the EvR cross sections are shown for the synthesis of elements 116, 117 and 119 formed in fusion reactions of ^{48}Ca with ^{250}Cm, ^{249}Bk and ^{254}Es targets.

In accordance with our calculations of decay properties of SH nuclei [22], the isotopes ^{291}115 and ^{291}114 may experience not only α decay but also electron capture with half-life of several seconds. If it is correct, the narrow pathway to the middle of the island of stability is surprisingly opened by the 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. 3. 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. However, for the moment, this is the only method which is proposed for the production of SH nuclei located just in the middle of the island of stability.

4 Production of SH Nuclei in Multi-Nucleon Transfer Reactions

Due to the bending of the stability line forwards the neutron axis, in all fusion reactions only *proton rich* SH nuclei with a short half-life can be produced located far from the island of stability (see Fig. 2). The multi-nucleon transfer processes in low-energy collisions of heavy (and very heavy, U-like) nuclei could be quite practicable for the production of new neutron rich isotopes of SH elements [23]. Additional enhancement of the corresponding cross sections may originates here due to the shell effect. We called it "inverse quasi-fission" process [23]. In this process one of the heavy colliding partners, say ^{238}U, transforms to lighter doubly magic nucleus ^{208}Pb while the other one, say ^{248}Cm, transform to the complementary SH nucleus. The role of these shell effects in damped collisions of heavy nuclei is still

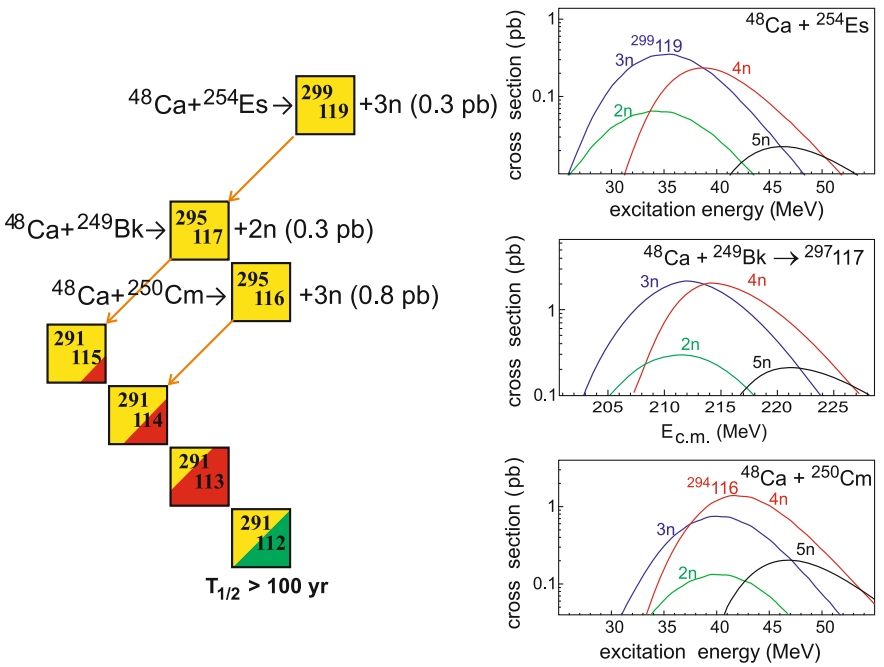

Fig. 3 Production cross sections of elements 116, 117 and 119 in the fusion reactions of ^{48}Ca with ^{250}Cm, ^{249}Bk and ^{254}Es targets. The numbers near the *curves* indicate the corresponding neutron evaporation channels. The possible pathway to the middle of the island of stability via a β^+ decay of the isotopes ^{291}115 and ^{291}114 is shown

not absolutely clear and was not carefully studied experimentally. However very optimistic experimental results were obtained recently [24] confirming such effects in the ^{160}Gd+^{186}W reaction, for which the similar "inverse quasi-fission" process (^{160}Gd→ ^{138}Ba while ^{186}W→ ^{208}Pb) has been also predicted [25].

In multi-nucleon transfer reactions the yields of SH elements with masses heavier than masses of colliding nuclei strongly depend on the reaction combination. For example, the cross sections for the production of Fermium isotopes in the U+Cm combination are two orders of magnitude larger as compared with the U+U combination [26]. We found that the cross sections for the production of *neutron rich* transfermium isotopes in reactions with ^{248}Cm target change sharply if one changes from medium mass (even neutron rich) projectiles to the uranium beam. In Fig. 4 the charge and mass distributions of heavy primary reaction fragments are shown for near barrier collisions of ^{238}U, ^{136}Xe and ^{48}Ca with curium target. The "lead shoulder" manifests itself in all these reactions. However, for ^{136}Xe+^{248}Cm and ^{48}Ca+^{248}Cm collisions it corresponds to the usual (symmetrizing) quasi-fission process in which nucleons are transferred mainly from the heavy target (here it is ^{248}Cm) to the lighter projectile. This is a well studied process both experimentally [27] and theoretically [28]. It is caused just by the shell effects leading to the deep lead valley on the multi-

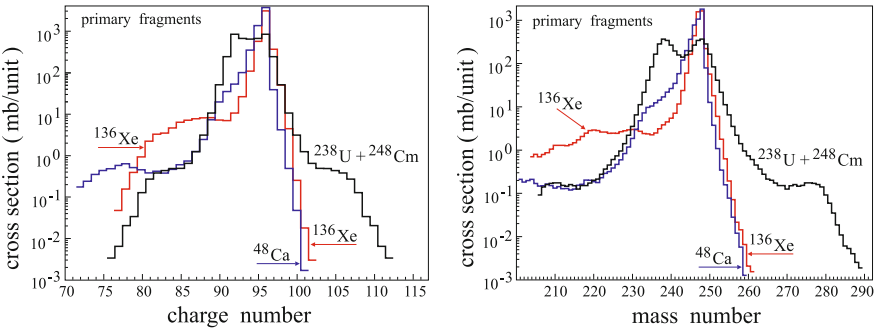

Fig. 4 Charge and mass distributions of heavy primary reaction fragments formed in collisions of ^{238}U, ^{136}Xe and ^{48}Ca with ^{248}Cm target at $E_{\text{c.m.}} = 750$, 500 and 220 MeV, correspondingly

dimensional potential energy surface which regulates the dynamics of the heavy nuclear system at low excitation energies.

Contrary to this ordinary quasi-fission phenomena, for the ^{238}U+^{248}Cm collisions we may expect an inverse process in which nucleons are predominantly transferred from the lighter partner (here is uranium) to heavy one (i.e. U transforms to Pb and Cm to 106 element). In this case, besides the lead shoulder in the mass and charge distributions of the reaction fragments, there is also a pronounced shoulder in the region of SH nuclei (see Fig. 4).

Of course, the yield of survived SH elements produced in the low-energy collisions of actinide nuclei is rather low, though the shell effects give us a definite gain as compared to a monotonous exponential decrease of the cross sections with increasing number of transferred nucleons. In Fig. 5 the calculated EvR cross sections for the

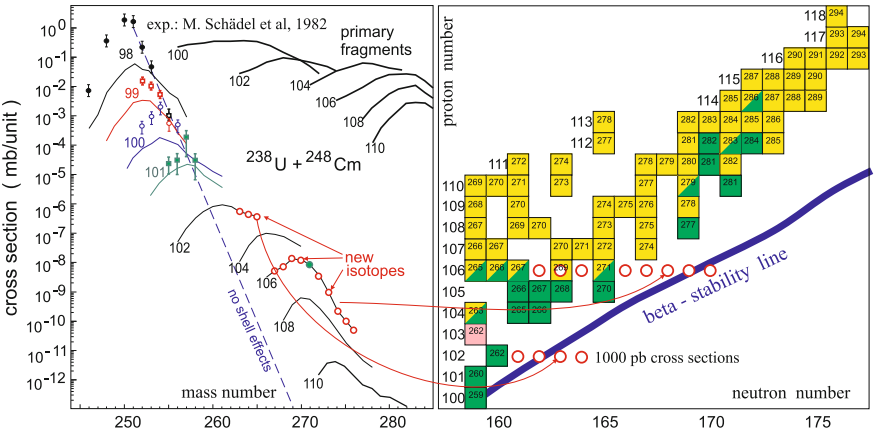

Fig. 5 Yield of survived isotopes of SH nuclei produced in collisions of ^{238}U with ^{248}Cm target at $E_{\text{c.m.}} = 750$ MeV

production of SH nuclei in damped collisions of ^{238}U with ^{248}Cm at 750 MeV center-of-mass energy are shown along with available experimental data. As can be seen, really many new neutron-rich isotopes of SH nuclei with $Z > 100$ might be produced in such reactions.

The choice of collision energy is very important for the production of desired neutron-rich SH nuclei. With increasing beam energy the yield of primary fragments increases. However the excitation energy of these fragments also increases and thus decreases their survival probabilities. We found that the optimal beam energy for the production of neutron-rich isotopes of SH elements in multi-nucleon transfer reactions with heavy actinide nuclei (like U+Cm) is very close to the energy needed for these nuclei to reach the contact configuration (there is no ordinary barrier: the potential energy of these nuclei is everywhere repulsive). For ^{238}U+^{248}Cm it is about 750 MeV center-of-mass collision energy.

5 Nucleosynthesis by Neutron Capture

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 at the beta 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 predict also another region of short-living nuclei located at $Z = 106 \div 108$ and $A \sim 270$.

The synthesis of heavier nuclei in the reaction of neutron capture with subsequent beta-minus decay is a well studied process. Relative yields of the isotopes formed in such a process may be found as a solution of the following set of differential equations (somewhat simplified here)

$$\frac{dN_{Z,A}}{dt} = N_{Z,A-1} n_0 \sigma_{n\gamma}^{Z,A-1} - N_{Z,A} n_0 \sigma_{n\gamma}^{Z,A} - N_{Z,A}[\lambda_{Z,A}^{\beta-} + \lambda_{Z,A}^{fis} + \lambda_{Z,A}^{\alpha}] + N_{Z-1,A}\lambda_{Z-1,A}^{\beta-} + N_{Z+2,A+4}\lambda_{Z+2,A+4}^{\alpha}, \quad (1)$$

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 the channel i (i.e., beta-minus, alpha decays and fission). 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 the value of about 1 barn, which is used below for numerical estimations.

To solve Eq. (1) numerically one needs to know the decay properties of neutron rich nuclei which are not studied yet experimentally. This is the key problem, which significantly complicates any analysis of the multiple neutron capture processes. The details of calculations of the decay properties of heavy and SH nuclei can be found in [22].

In Fig. 6 the experimental data on the yield of transuranium nuclei in the test thermonuclear explosion "Mike" [29] (left panel) are compared with those calculated by Eq. (1) assuming 1 μs neutron exposure of 1.3×10^{24} neutrons/cm^2 with subsequent one-month decay time. Note that elements 99 and 100 (einsteinium and fermium) were first discovered just in debris of the "Mike" explosion. As can be seen, in this case the Fermium gap does not influence the yields of nuclei with $Z > 100$.

The resulting charge number of the synthesized nuclei might be significantly increased by sequential neutron flux exposure if two or several nuclear explosions would be generated in close proximity of each other. This natural idea was already discussed many years ago [30]. At that time the experts (such as Edward Teller) concluded that technically it could be realized. Such a process is illustrated in the left panel of Fig. 6. In the right panel of this figure the probabilities of heavy element formation are shown for one, three and ten subsequent short-time (1 μs) neutron exposures of 10^{24} n/cm^2 each following one after another within a time interval of 10 s with final one month waiting time (needed to reduce the strong radioactivity of the produced material and to perform some experimental measurements).

We found that the result depends both on the neutron fluence $n = n_0\tau$ (τ is the duration of explosive neutron irradiation) 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 ÷ 108 and A∼270. Dependence on the time interval between two exposures is not so crucial. The result does not almost depend on this parameter if it is longer than several milliseconds (to avoid approaching the neutron drip line after several

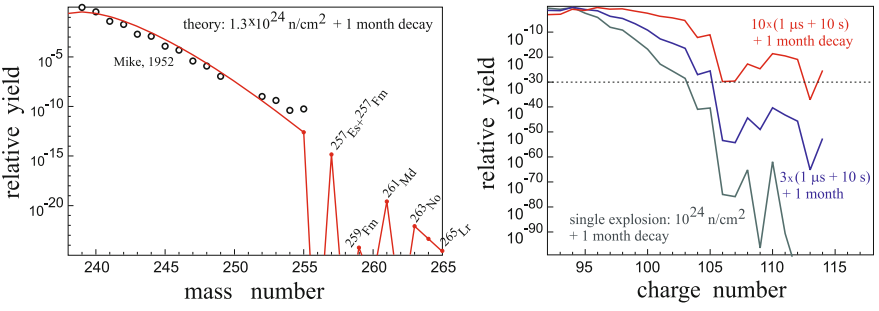

Fig. 6 Experimental (*open dotes*) and calculated relative yields of heavy nuclei in the test nuclear explosion "Mike" [29] (*left panel*). Probability for formation of heavy nuclei in multiple neutron irradiation of initial ^{238}U material (one, three and ten subsequent explosions). The *dotted line* denotes the level of few atoms

exposures) and shorter than a few minutes to avoid β^--decay of the produced nuclei into 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 be really used for the production of a noticeable (macroscopic) amount of neutron rich long-lived SH nuclei. Leaving aside any discussions on the possibility of such processes and associated technical problems, we want to emphasize a sharp increase of the probability for formation of heavy elements with $Z \geq 110$ in the multiple neutron irradiations: enhancement by several tens of orders of magnitude (see Fig. 6). This probability is high enough for some SH elements to perform their experimental identification.

It is interesting also 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 (up to few milliseconds). However, the neutron fluence usually does not exceed 10^{16} n/cm^2 in existing nuclear reactors. Multi-pulse irradiation here corresponds, in fact, to the "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.

The situation may change if one could be able to increase somehow the intensity of the pulsed reactor. The neutron fluence in one pulse and frequency of pulses should be high enough to bypass both gaps of short-lived nuclei on the way to the island of stability. Thus, the specification of the high-intensity pulsed reactors of next generation depends strongly on properties of heavy neutron rich nuclei located to the right of these gaps. These nuclei are not discovered yet, and undoubtedly certain experimental efforts should be made to resolve this problem. We have found that increase of the neutron fluence in the individual pulse by about three orders of magnitude as compared with existing pulsed reactors, i.e. up to 10^{20} neutrons/cm^2, could be quite sufficient to bypass both gaps.

6 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 such a process some amount of SH elements of the island of stability might be also 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 which follow core-collapse supernova explosions [31] or by the mergers of neutron stars [32]. Estimation of relative yields of SH elements is a difficult problem which depends both on the features of neutron fluxes and on the experimentally unknown decay properties of heavy neutron rich nuclei.

We made a very simple estimation of the possibility for formation of SH nuclei during the astrophysical r-process of neutron capture. This estimation is based on the following assumptions. (1) SH nuclei are relatively short-living. They are absent in stars initially, while the distribution of other elements is rather close to their abun-

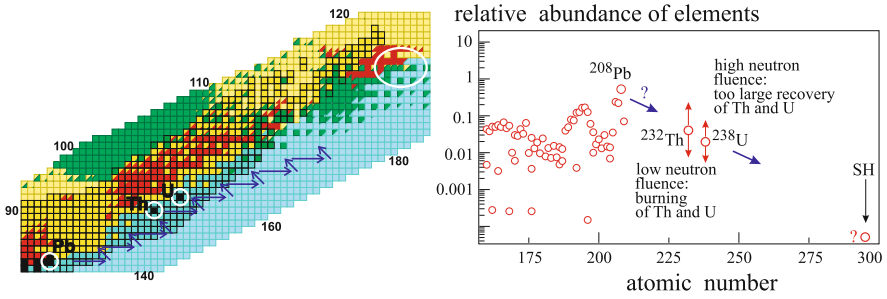

Fig. 7 Formation of SH elements in astrophysical r-process. Unknown neutron fluence could be adjusted in such a way that relative abundances of uranium and thorium (burned and recovered from lead and lighter stable elements) keep finally their experimental values

dance in the universe. (2) SH nuclei may appear (and survive) at 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. (3) Existing (experimental) abundance of stable nuclei may be used as initial condition. During intensive neutron irradiation initial thorium and uranium material are depleted transforming to heavier elements and going to fission, while more abundant lead and lighter stable elements enrich thorium and uranium. (4) Unknown total neutron fluence may be adjusted in such a way that the ratios Y(Th)/Y(Pb) and Y(U)/Y(Pb) keep its 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 [22], their half-lives are about several hundred years).

We performed calculations (Fig. 7) starting from initial relative abundances of heavy elements corresponding to experimental values. The value of the neutron flux n_0 was fixed at 10^{24} cm^{-2}sec^{-1} and the total neutron fluence was regulated by the time of exposure. At such high neutron flux the final result depends only on the total neutron fluence. After neutron irradiation the waiting time of 100 years was applied to obtain the final distribution of nuclei after all the decays. This time is still shorter than 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. At low neutron fluxes initial thorium and uranium nuclei increase their masses and charges (after neutron capture and subsequent β^--decay), find themselves in the region of fission instability and drop out. Thus, their numbers decrease relative to lead, which, in contrast with Th and U, has an additional feed from lighter nuclei. Contribution from lead to thorium and uranium becomes noticeable only when the probability for capture of 24 neutrons is not negligible. At neutron fluence $n \sim 1.5 \cdot 10^{25}$ cm^{-2} (= 15 neutrons/barn) burning of thorium and uranium is compensated by increasing contribution from lighter stable nuclei with $Z \leq 83$. However at this neutron fluence the final abundance of thorium and uranium is still too low, and only at $n \sim 2 \cdot 10^{25}$ cm^{-2} the both ratios Y(Th)/Y(Pb) and Y(U)/Y(Pb) are close to

the observed values. At this neutron fluence the relative to lead yield of most stable isotopes of SH element 112, namely ^{291}Cn and ^{293}Cn, is about 10^{-12} which is not extremely low and keeps hope to find them in nature (most probably in the cosmic rays).

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