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Formation of Super-Heavy Elements in Astrophysical Nucleosynthesis

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Abstract. The unexplored area of heavy neutron-rich nuclides is extremely important for the understanding of the *r* process of astrophysical nucleogenesis. For elements with Z>100 only neutron deficient isotopes (located to the left of the stability line) have been synthesized so far. The "north–east" area of the nuclear map can be reached neither in fusion reactions nor in fragmentation processes. Low energy multi-nucleon transfer reactions are quite promising for the production and study of neutron-rich heavy nuclei including those located at the superheavy (SH) island of stability [1]. The neutron capture process is considered here as an alternative method for the production of SH nuclei. Requirements for the pulsed reactors of the next generation that could be used for the synthesis of long-living neutron rich SH nuclei are formulated. Formation of SH nuclei in supernova explosions is also discussed and the abundance of SH elements in nature is estimated.

Keywords: superheavy elements, neutron capture, nuclear reactors, supernova explosions
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ISLANDS OF STABILITY ON THE NUCLEAR MAP

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 the sharp increase of 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 subsequent regions of stability of SH nuclei were predicted to originate by the next neutron and proton closed shells at $Z \sim 114$ and $Z \sim 164$ [2]. Many attempts to find more or less stable SH elements in nature were not succeeded yet [3]. "Cold" fusion reactions lead to the production of proton rich isotopes of SH elements located far from the beta-stability line [4, 5]. 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 (see, e.g., [6]). Such a possibility has been realized only recently. The isotope ^{285}Cn, observed in the decay chains of SH nuclei ^{289}114 and ^{293}116 produced in the ^{48}Ca+^{244}Pu [7] and ^{48}Ca+^{248}Cm [8] fusion reactions, reveals very long half-life of about 30 seconds. This is 5 orders of magnitude longer as compared with the half-life of more neutron deficient isotope ^{277}Cn produced in the "cold" fusion reaction [4]. This fact evidently confirms an existence of the island of stability. However, one needs to add six to eight more neutrons to reach the most stable SH nuclei of this island, which is impossible in any fusion reactions of stable beams with available targets.

The 10-years epoch of ^{48}Ca irradiation of actinide targets for the synthesis of SH elements is almost over. The heaviest available target of californium ($Z = 98$) had been used to produce the element 118 [9]. This projectile still could be successfully used

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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 corresponding cross sections are rather high to perform these experiments at available facilities [10]. Note, that the earlier predicted more or less constant values (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 [11, 12] have been fully confirmed by the experiments performed in Dubna, in Berkeley [13] and at GSI [14].

To get SH elements with $Z > 118$ in fusion reactions, one should proceed to projectiles heavier than ^{48}Ca. The use of ^{50}Ti beam instead of ^{48}Ca decreases the yield of SH nuclei by about factor 20 due to a worse fusion probability [15]. The estimated cross sections for the 119 and 120 SH elements synthesized in the ^{50}Ti induced fusion reactions are rather low (~ 0.05 pb) [15]. The synthesis of these nuclei may encounter also another important problem. The proton rich isotopes of these elements produced in fusion reactions are short-living due to large values of Q_α. Their half-lives are very close to the critical value of one microsecond needed to pass through the separator up to the focal plane detector. The elements with $Z > 120$ being synthesized in such a way might be already beyond this natural time limit for their detection (see the left panel of Fig. 1).

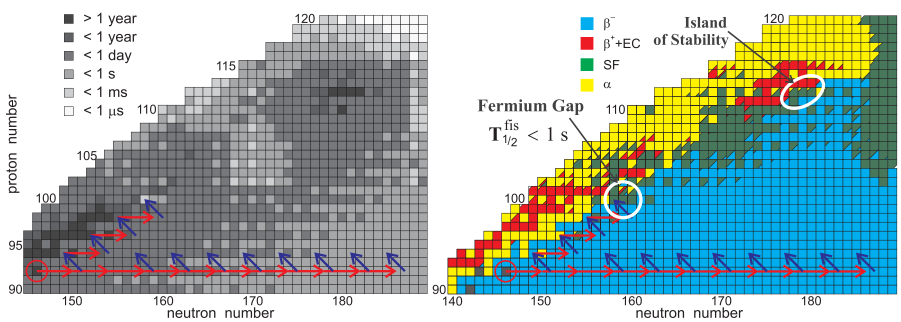

FIGURE 1. Calculated half-lives and preferable modes of decay of nuclei in the upper part of the nuclear map. Slow and fast neutron capture processes with subsequent β^- decays are shown by arrows.

SYNTHESIS OF SH NUCLEI BY NEUTRON CAPTURE

The neutron capture process is an alternative (oldest and natural) method for the production of heavy elements. Strong neutron fluxes might be provided by nuclear reactors and nuclear explosions under laboratory conditions and by supernova explosions in nature. The "fermium gap," consisting of the isotopes $^{258-260}$Fm located on the stability line and having very short half-lives for spontaneous fission, impedes the formation of nuclei with Z>100 in existing nuclear reactors. In nuclear and supernova explosions this gap may be bypassed, if the total neutron fluence is high enough. Note that elements 99 and 100 (Es and Fm) were first discovered in debris of the test nuclear explosion "Mike".

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 [16]. However, no quantitative estimations have been done for the yields of SH neutron rich nuclei in such processes. In Fig. 2 the probabilities of heavy element formation are shown for several subsequent short-time (1 μs) neutron exposures of 10^{24} n/cm^2 each following one after another within a time interval of 10 seconds. Thus, multiple rather "soft" nuclear explosions could really be used for the production of a macroscopic amount of neutron rich long-living SH nuclei. One has to emphasize the sharp increase in the probability of formation of SH elements with Z$\geq$110 in multiple-neutron irradiations: enhancement by *several tens of orders* of magnitude.

The same process might be also realized in pulsed nuclear reactors. Here the pulse duration is much longer. However, the neutron fluence usually does not exceed 10^{16} n/cm^2 in existing nuclear reactors, the time of neutron capture $\tau_n = (n_0\sigma_{n\gamma})^{-1} \sim 10^5$ s, and only the nearest long-living isotopes of irradiated elements can be formed which 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 the intensity of the pulsed reactor. The neutron fluence of one pulse and frequency of pulses should be high enough to bypass two gaps of short living nuclei on the way to the island of stability (see Fig. 1). The specifications of the high–intensity pulsed reactors of the next generation depends strongly on properties of heavy neutron rich nuclei. We have found that increase of the neutron fluence by about three orders of magnitude, i.e. up to 10^{20} neutrons/cm^2, could be quite sufficient to bypass both gaps [17].

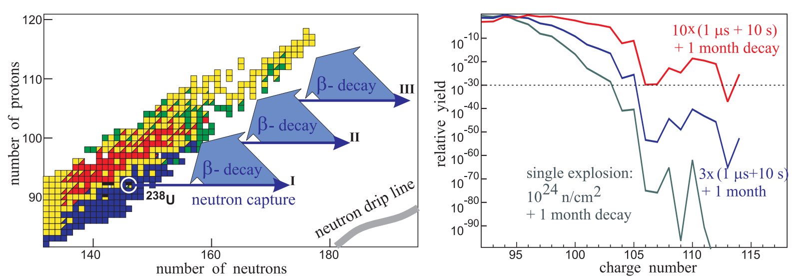

FIGURE 2. Schematic picture for multiple neutron irradiation of initial ^{238}U material (left) and probability for formation of heavy nuclei in such processes (one, three and ten subsequent explosions).

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. Strong neutron fluxes are expected to be generated by neutrino-driven proto-neutron star winds which follow core-collapse supernova explosions or by the mergers of neutron stars. 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 performed a simple estimation of the possibility for formation of SH nuclei during 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 close to their abundance in the universe. (2) SH nuclei may appear at the last stage of the astrophysical r process when the observed abundance of heavy elements (in particular, Th and U) is also reproduced. (3) During intensive neutron irradiation initial Th and U material are depleted transforming to heavier elements and going to fission, while more abundant Pb and lighter stable

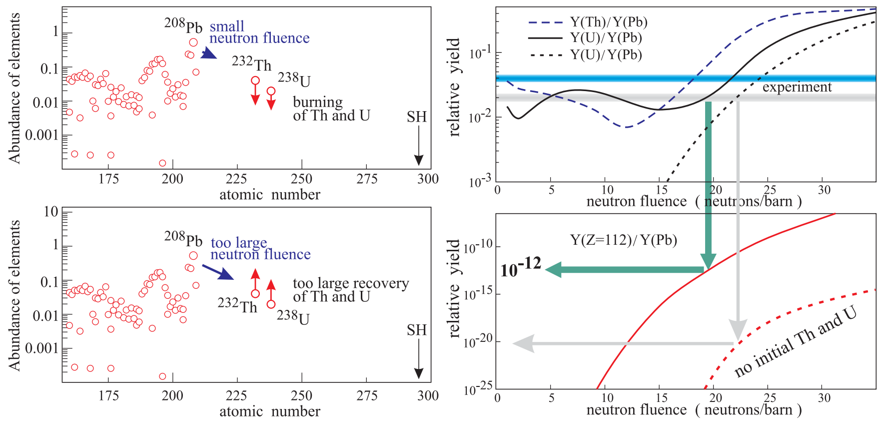

FIGURE 3. Burning and recovery of Th and U nuclei are shown schematically on the right panel. Relative yields of Th (dashed) and U (solid curve) depending on neutron fluence in astrophysical *r* process are shown on the top right panel. The horizontal bars show experimental values of thorium and uranium abundances. The same for relative yield of long-living SH copernicium isotopes ^{291,293}Cn (right bottom).

elements enrich Th and U. (4) Unknown neutron fluence is adjusted in such a way that the ratios Y(Th)/Y(Pb) and Y(U)/Y(Pb) reach their experimental values at the end of the process. This neutron fluence defines simultaneously the relative yield of SH elements.

The results of our calculations are presented in the right panels of Fig. 3, where the relative to Pb yields of Th, U and long-living copernicium (Z=112) isotopes are shown depending on the total neutron fluence. At neutron fluence $n \sim 1.5 \cdot 10^{25}$ cm^{-2} burning of Th and U is compensated by increasing contribution from lighter stable nuclei with $Z \leq 83$, and at $n \sim 2 \cdot 10^{25}$ cm^{-2} are both ratios, Y(Th)/Y(Pb) and Y(U)/Y(Pb), close to the observed values. At this neutron fluence the relative to lead yield of most stable isotopes of SH element 112, namely ^{291,293}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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