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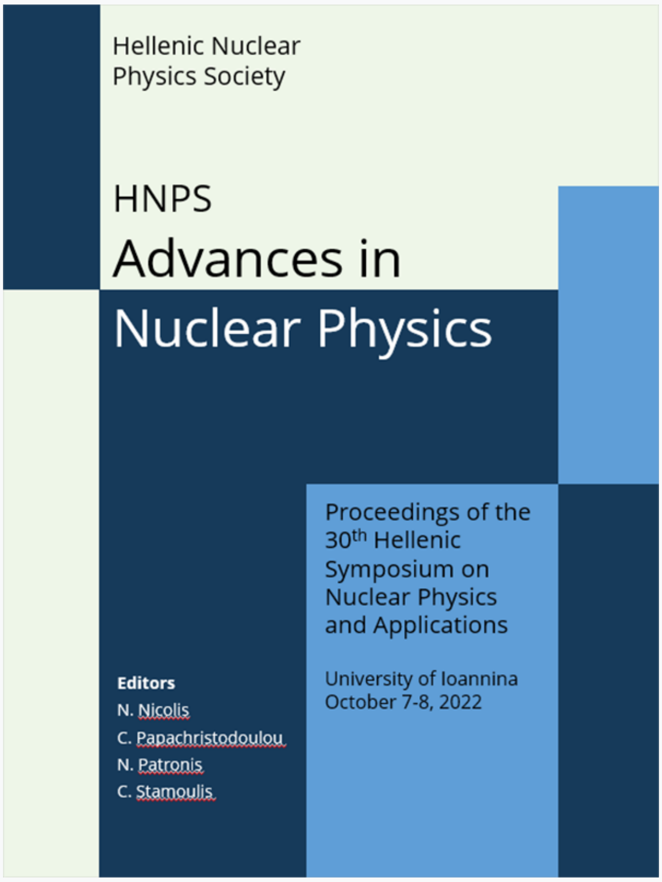

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Investigating the possible existence of hyper-heavy nuclei in a neutron-star environment

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Abstract The synthesis of hyper-heavy elements is investigated under conditions simulating neutron star environment. The constrained molecular dynamics approach is used to simulate low energy collisions of extremely *n*-rich nuclei. A new type of the fusion barrier due to a "neutron wind" is observed when the effect of neutron star environment (screening of Coulomb interaction) is introduced implicitly. When introducing also a background of surrounding nuclei, the nuclear fusion becomes possible down to temperatures of 10^8 K and synthesis of extremely heavy and *n*-rich nuclei appears feasible. A possible existence of hyper-heavy nuclei in a neutron star environment could provide a mechanism of extra coherent neutrino scattering or an additional mechanism, resulting in x-ray burst or a gravitational wave signal and, thus, becoming another crucial process adding new information to the suggested models on neutron star evolution. These proceedings are part of a paper that has already been published and the relevant reference is: M. Veselský et al., PRC 106, L012802 (2022).

Keywords Neutron star, hyper-heavy elements, fusion

INTRODUCTION

We know today that the heaviest elements with $Z = 114$–118 were produced in hot fusion reactions with emission of 3–4 neutrons using ^{48}Ca beams and heavy actinide targets between uranium and californium [1]. The main obstacle for the production of such nuclei is a fusion hindrance caused by competition of a fusion process with an alternative process called quasifission. Quasifission occurs, when instead of fusion, the system separates into two fragments and thus constitutes the principal obstacle to the production of heavier nuclei in laboratory conditions. While such an obstacle can be hardly circumvented in the physical laboratory, there exist environments, namely neutron stars, where, in electrically neutral neutron matter, the effect of the repulsive Coulomb force can practically vanish. Such collisions, even at low energy, can in principle be simulated, potentially leading to hyper-heavy nuclei in the interior of a neutron star. Thus, exotic configurations with Z>120 are hardly relevant to terrestrial (laboratory) experiments, but they can exist in neutron-rich environments included the atmosphere of stellar explosions and the compositions of neutron stars [2].

The creation and stability of superheavy and hyper-heavy nuclei in the form of bubbles or semibubbles (for a large array of proton and neutron numbers, $120<Z<340$ and $300<A<1000$) have been discussed also in [3]. In the seminal paper of Baym *et al.* [4], the authors found that, concerning the structure of the cold inner crust, for baryon densities $n_b > 0.006$ fm^{-3} ($\rho_0/30$) up to the crust-core transition $n_{tr}= 0.11$ fm^{-3} ($2\rho_0/3$ where ρ_0 is the typical value of the nuclear saturation density), the values of atomic and mass number are within the range $Z = 50$–200 and $A = 186$–2500, respectively. Other additional studies [5–7] have confirmed the results of [4]. An extensive discussion about the neutron star structure and properties both for cold and warm environment has been provided in [8,9]. In particular, in Chap. 14 of [9], Page and Reddy discussed the composition of the inner crust in the

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framework of mean field nuclear models, based on the Skyrme interaction. They show that the total number of nucleons per unit cell (containing one nucleus) reaches in all the considered cases very high values (Acell>100). Moreover, in a recent study [10], the authors, using the more elaborated χEFT Hamiltonian and the SLy4 phenomenological force, calculated the composition of the neutron star crust. In particular they predicted the cluster mass number Acl and proton number Zcl through the crust, with very high values for Acl and Zcl close to the crust-core interface (baryon density=0.1fm^{-3}).

The decompression of the inner crust, following the dynamically ejected mass after neutron star merger, has been discussed in [11]. In their calculations, nuclei up to $Z = 100$ were involved. All fusion reactions on light elements that play a role on nuclear statistical equilibrium are included. In addition, fission and β decays are also included. The authors concluded that matter from the inner crust of the coalescing NSs, which by far dominates the ejecta, producesan r-abundance distribution very similar to the solar one for nuclei with $A > 140$ [11]. In a notable study [12], Shen *et al.* constructed a large class of hot equations of state for use in astrophysical simulations of supernovae and neutron star mergers. In particular, they discussed the structure of inner crust in a relativistic mean field model with spherical Wigner-Seitz approximation, at finite temperature and proton fraction over a wide range of densities. They found that the average mass number A can be as large as 3000 at high density before the final transition to uniform matter.

According to the above discussion, theoretical studies suggest that the existence of nuclei with extremely high values of Z and A are possible. Consequently there is an open issue to investigate the possibility of a fusion process to take place in the environment of hot or/and cold neutron star crust. The instability of these superheavy nuclei is another issue worth studying. The existence of finite nuclei in neutron star environment is crucial for the solution of the problem of their cooling time, since the reactions with neutrinos can limit its cooling rate [13]. Ways of producing nuclei in neutron stars were summarized in [14], where a reaction network in a neutron star crust is described. Here, we investigate the conditions under which eventually hyper-heavy nuclei can be produced by fusion of very n-rich heavy nuclei using constrained molecular dynamics (CoMD) simulations. This might be a possible way to circumvent the limitations observed in the synthesis of hyper-heavy elements. Summarizing the existence of extremely n-rich nuclei, with N/Z ratios much higher than those experimentally observed nuclei, can be expected in a neutron star environment, where they will be surrounded by dilute neutron matter and their stability will depend on the balance of inward and outward flow of neutrons. Existence of such hyper-heavy nuclei was investigated recently in [15].

In this work, we investigate conditions of fusion in reactions leading to production of hyper-heavy nuclei up to $Z = 120$ and beyond. We note that using the Boltzmann-Uhling-Uhlenbeck (BUU) equation [16], it was possible to set a rather strict constraint on the parameters of the equation of state. The same parameters were obtained also when the CoMD transport code was used [17]. We thus consider feasible to use such an equation of state also for simulations of nucleus-nucleus collisions in a neutron star environment.We performed such calculations in the present work.

THEORETICAL MODEL

The CoMD model [18] has been used recently to describe the dynamics of low-energy phenomena. Studies incorporating reactions near the Fermi energy [19–22] and the fission of heavy nuclei [23,24] have been performed. The CoMD model is based on a two-body effective interaction with Skyrme potential characteristics which are written as

$$V_{\mathrm{vol}} = \frac{T_0}{\rho_0}\delta(r_i - r_j), \tag{1}$$

$$V_3 = \frac{2T_3\rho^{\sigma-1}}{(\sigma+1)\rho_0^{\sigma}}\delta(r_i - r_j), \tag{2}$$

$$V_{\text{sym}} = \frac{\alpha_{\text{sym}}}{\rho_0}\delta(r_i - r_j)\big(2\delta_{\tau_i,\tau_j} - 1\big), \tag{3}$$

$$V_{\text{sur}} = \frac{C_s}{\rho_0}\nabla^2_{\langle r_i\rangle}\delta(r_i - r_j), \tag{4}$$

$$V_{\text{coul}} = \frac{e^2}{||r_i - r_j||}. \tag{5}$$

In the above set of potentials, V_{vol} corresponds to the volume term, V_3 to the three-body term, V_{sym} to the symmetry term, and V_{sut} to the surface term, while Vcoul describes the Coulomb repulsion of the interacting protons. in this work, the parameters ρ_0, α_{sym}, and C_s are the saturation density, the symmetry, and surface parameter, respectively. Their values are fixed namely to $\rho_0 = 0.16$ fm^{-3}, $\alpha_{\text{sym}} = 32$ MeV, and $C_s/\rho_0 = 0$. The constants T_0, T_3, and σ are related to the compressibility of nuclear matter (NM) and are determined by the enforcement of the saturation condition of NM with the use of the effective interaction involving Eqs. (1) and (2). The one-body wave functions used in the model are Gaussian wave packets in the Wigner representation having the form

$$f(r,p) = \frac{1}{(2\pi\sigma_r\sigma_p)^3} e^{-\frac{(r-\langle r_j\rangle)^2}{2\sigma_r^2}} e^{-\frac{(p-\langle p_j\rangle)^2}{2\sigma_p^2}}. \tag{6}$$

The σ_r and σ_p are the widths, while $<r_j>$ and $<p_j>$ are the time dependent centroids of the wave packet of nucleon j in phase space. In the calculations presented below, $\sigma_r = 1.065$ fm and $\sigma_\rho\sigma_p$ = hbar/2.

SIMULATIONS

Simulations of reactions potentially leading to hyper-heavynuclei in the neutron star interior started a few years ago [16] using BUU, without Coulomb interaction assuming the presence of electrons and thus charge neutrality. We assumed neutron-rich nuclei with $N/Z = 4$, 140Ni+460U in particular. This reaction is analogous to reaction 64Ni+238U, with the highest proton number among the reactions investigated, focusing on reactions, leading to experimentally observed superheavy nuclei. The choice of $N/Z = 4$ corresponds to expected proton fractions in a neutron star environment. Such BUU simulations observed no fusion barrier except for a repulsive "neutron wind" caused by the emission of nucleons, which can prevent contact of nuclei in the otherwise empty space and thus fusion. This effect appears stronger for stiff symmetry energy. It is assumed that n-rich nuclei exist in the inner crust of protoneutron stars, and their fusion (and eventually formation of hyper-heavy nuclei) can affect cooling due to coherent neutrino scattering. The reactions of nuclei in an inhomogeneous medium [25] can be strongly influenced by a proton fraction and distribution of electrons assuring overall neutrality. There is no *a priori* reason why electrons (electron fluid) could not enter the nucleus, especially since the calculated Debye-Hückel length amounts to a few fm. Possible distribution of charge in nuclei can thus remind a so-called plasma mirror on the surface of nuclei, with an excess of electrons outwards and excess of protons inside. In this way, the Coulomb interaction will act only at close distance of few fm as given by the Debye-Hückel length

$$\lambda_D = \sqrt{\frac{\epsilon_0}{n_e q_e^2/T_e + n_p q_p^2/T_p}}. \tag{7}$$

The Debye-Hückel length is determined by densities (np,e) and temperatures (Tp,e) of both protons and electrons. The simulations have control of the density and temperature of protons, while the density of electron fluid can be assumed equal to the density of protons, even if local deviations are possible, especially around the surface and in the interior of nuclei. The temperature of electron fluid (and thus the localization of electrons) can be considerably higher than the temperature of protons. Thus we choose the value of the Debye-Hückel length by the density and assumed temperature of proton gas within the nucleonic background, the latter taken equal to the beam energy. The Debye-Hückel formula used in this work assumes classical protons. This approximation can be justified for lowest values of density of the proton background, where, assuming temperature of around 1 MeV, it is comparable to Fermi energy. Even for the largest assumed proton densities, the Debye-Hückel formula yields values of proton screening length comparable to the Thomas-Fermi formula assuming zero temperature. The approximation used for proton screening thus appears as reasonable. The impact parameter is chosen between 0 and 1 fm, as in previous simulations leading to the synthesis of superheavy nuclei. However for energies comparable to temperatures below a few MeV, all the possible reactions proceed within an *s* wave, and thus the fusion probabilities will be the same.

A. Without nucleonic medium

Recently the CoMD code was modified to include Coulomb screening via an interaction cutoff at a distance corresponding to the Debye-Hückel length. The simulations were performed with the CoMD code, using the equation of state (EoS) with K_0 = 254 MeV, which was found to be optimal for the description of reactions leading to the synthesis of superheavy nuclei in the laboratory [17]. The time step was 1 fm/c and the charge screening effect of surrounding nuclear medium in the neutron star was simulated by implementing a cutoff, limiting the range of the Coulomb interaction to 2 fm. This corresponds approximately to the density of surrounding nucleonic medium amounting to $\rho_0/5$. Fusion barrier was observed between 1.25 MeV and 1.5MeV/nucleon (see Fig. 1) due to a 'neutron wind" even with Coulomb interaction cutoff of 2 fm. The turning point is at distances exceeding the range of such screened Coulomb interaction. Long term survival up to 30000 fm/c was also investigated, using again 140Ni+460U at very low kinetic energy (a value 6 keV was chosen and the Coulomb interaction cutoff was set at 1 fm). A long term stability was observed for both soft and stiff symmetry energy, even if for stiff symmetry energy nuclei are more unstable against emission of nucleons, causing the observed "neutron wind", which is stronger than in the case of soft symmetry energy. Such behavior is observed up to a Coulomb interaction cutoff of 10 fm. Above such value, the Coulomb interaction starts to dominate and nuclei become unstable against fission or fragmentation into more parts.

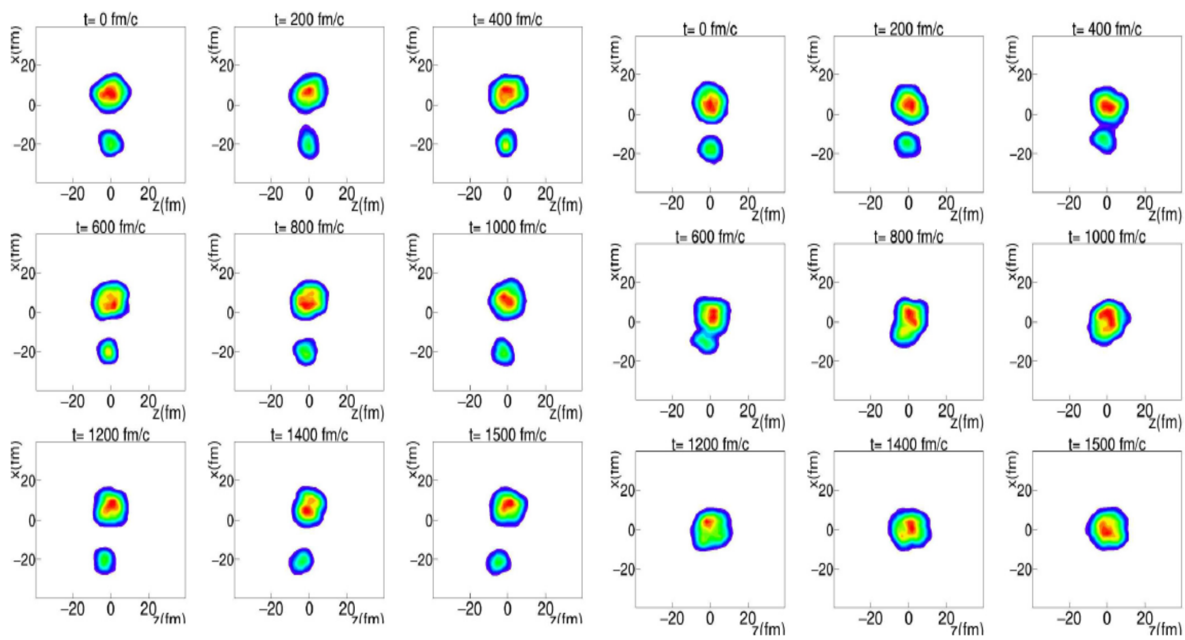

Figure 1. *Typical evolution of nucleonic density for central collision 140Ni+460U calculated using the CoMD code at beam energy 1.25MeV/nucleon (left panel) and 1.5MeV/nucleon (right panel). A Coulomb interaction cutoff 2 fm, incompressibility K_0 = 254MeV and a soft density dependence of symmetry energy were used. Scattering due to a "neutron wind" dominates at lower beam energy (left panel), while fusion dominates at higher beam energy (right panel).*

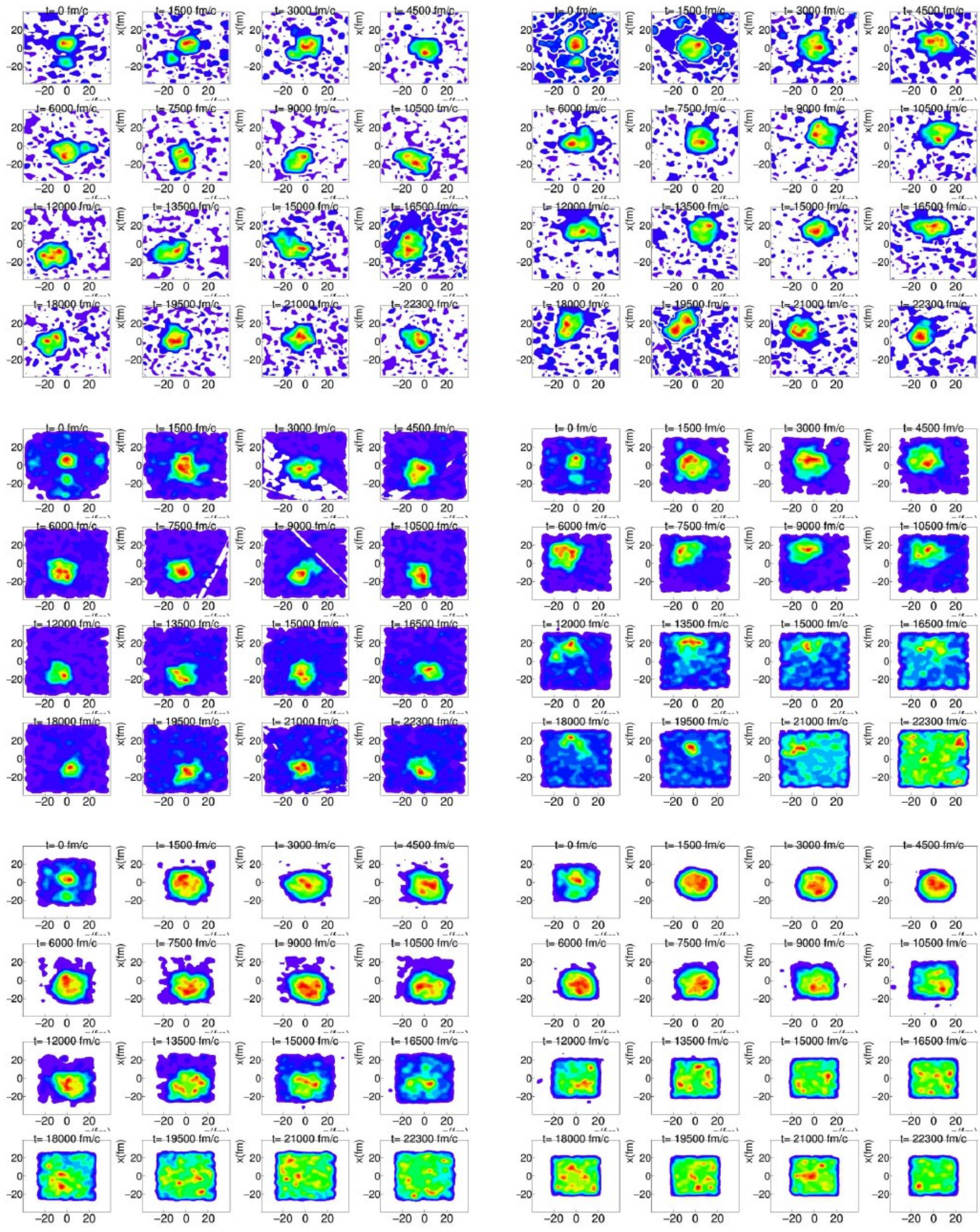

Figure 2. *Evolution of the system 140Ni+460U in the nucleon bath with 10% proton concentration calculated using the CoMD code at beam energy 0.01MeV/nucleon and Coulomb interaction cutoff at 10, 7, 5, 4, 3, and 2 fm (from top to bottom and left to right), corresponding to nucleon bath densities $\rho_0/100$, $\rho_0/50$, $\rho_0/30$, $\rho_0/17$, $\rho_0/10$, and $\rho_0/5$, respectively. Incompressibility is K_0 = 254MeV and a soft density dependence of symmetry energy were used. The initial distance is 25 fm. On the time scale up to 25000 fm/c the resulting nucleus appears to dissolve in the nucleon bath with density above $\rho_0/30$, even sooner with increasing density.*

B. With nucleonic medium

To simulate conditions inside neutron stars, CoMD was further modified to introduce a low density nucleonic background by placing 2000 nucleons inside a box with periodic boundary conditions. The size of the box was initially set to 50 × 50 × 50 fm3, corresponding to approximately one-tenth of saturation density. The cutoff of the Coulomb interaction was set correspondingly to the Debye-Hückel length at given density and proton fraction of nuclear medium (10%). The simulations lead to the confirmation that the "neutron wind" observed previously was unphysical and practically there is no fusion barrier down to beam energy corresponding to typical neutron star temperature 108–109 K (10–100 keV). An interesting new observation is that besides fusion, there exists another mechanism for the growth of nuclei, since for soft (γ = 0.5, Fig. 2) and intermediate (γ = 0.75) symmetry energy the resulting compound nucleus captures and incorporates nearly all nucleons of the background in the box. This signals an instability which could lead to a significant presence of very heavy nuclei in a neutron star interior, especially prior to cooling down to equilibration temperature where this distribution of nuclear sizes will follow a statistical law. For stiff symmetry energy (γ = 1.0), such effect is much weaker if any at all. Thus the symmetry energy can play an additional role in the structure of protoneutron stars and their cooling rate.

C. Final simulations

Besides a background density of one-tenth of the saturation density, lower and higher background densities were explored, with the range of Coulomb interaction adjusted to the corresponding Debye-Hückel length. The effect of a collapse of background nucleons into compound nucleus is preserved also at background density one-fifth of saturation density, while it disappears at lower background densities. Concerning the nature of such collapse, it is most probably connected to the first order phase transition in nuclear matter, where the density dependence of symmetry energy controls the extent of the spinodal region in the isovector plane. In order to estimate a possible effect of such reactions on the structure and properties of a neutron star, the simulations were run for longer time up to 25000 fm/c (10−20 s). If the formed compound nucleus survives for such time, it will have enough time to travel to a neighboring cell, where an analogous reaction can occur, and cause further reaction with a neighboring compound nucleus, thus forming even an heavier system. Such a scenario is supported by the work [12], where fractions of heavy nuclei up to 70% are predicted in the density range $\rho_0/5$–$\rho_0/50$.

The simulations in Fig. 2 were performed using a kinetic energy of 10 keV in the c.m. frame, but similar results were obtained also for beam energies of few MeV, corresponding to analogous temperatures. This can be naturally expected when considering that the total energy of the system remains essentially the same. It appears that a temperature above 1MeV might be sufficient to provide reaction products with sufficient mobility to support the fusion reaction cascade and a formation of a heavier system. Such temperatures can be explained not only on protoneutron stars [26–28], but also in cold stable neutron stars [29]. The results of simulations are shown in Fig. 2 for a soft parametrization of the density dependence of symmetry energy. The simulations for medium and stiff parametrization of symmetry energy, are also performed and they are available in the Supplemental Material [30]. On the time scale up to 25000 fm/c for the soft and medium symmetry energy parametrization, the resulting nuclei appear to dissolve in the nucleon bath with density above $\rho_0/30$, and even sooner with increasing density. For lower densities the resulting nuclei appear to survive long enough to reach neighboring cells and collide with their equivalent nuclei there.

For a stiff parametrization of the symmetry energy, the behavior is similar at high densities, however, at lowest density, the onset of fission can be observed, thus reverting the possible fusion reaction cascade. Still, a maximum of lifetime can be observed between densities $\rho_0/30$ and $\rho_0/50$, where a fusion reaction cascade may be supported. A similar maximum of lifetimes could be possibly observed for softer symmetry energy parametrizations at longer times. The above simulations were performed at a proton fraction of 10%. Increasing or decreasing the proton fraction will mean corresponding decreasing or increasing the Debye-Hückel length by the square root of the relative increase (decrease) of the proton fraction. This variation can affect the simulations only moderately within the expected proton fractions between a few percent up to 20%, possibly shifting the optimum density slightly below or above, respectively.

CONCLUSIONS

The synthesis of hyper-heavy elements was investigated under conditions simulating a neutron star environment. The CoMD approach was used to simulate the low energy collisions of extremely *n*-rich nuclei. A new type of the fusion barrier due to a "neutron wind" has been observed, when the effect of a neutron star environment (screening of Coulomb interaction) was introduced implicitly. When introducing also a nucleonic background of surrounding nuclei, fusion becomes possible down to temperatures 108 K and the synthesis of extremely heavy and *n*-rich nuclei appears feasible.

Specifically, in this work, the evolution of a hyper-heavy system consisting of 140Ni+460U in a nucleon bath with 10% proton concentration was calculated using the CoMD code at beam energy from 10 keV to 1MeV. Coulomb interaction screening was introduced by a cutoff at 10, 7, 5, 4, 3, and 2 fm, corresponding to nucleon bath densities $\rho_0/100$, $\rho_0/50$, $\rho_0/30$, $\rho_0/17$, $\rho_0/10$, and $\rho_0/5$, respectively. An EoS with incompressibility K_0 = 254MeV was used. Using a soft, medium, and stiff density dependence of symmetry energy, on the time scale up to 25000 fm/*c*, the resulting nucleus appeared to dissolve in the nucleon bath with density above $\rho_0/30$, even sooner with increasing density. In addition, for a stiff density dependence of symmetry energy and at lowest density, the fission appears to take over, thus suggesting a maximum of lifetime between densities $\rho_0/50$ and $\rho_0/30$, sufficient to support a fusion cascade.

We suggest that this possible existence of hyper-heavy nuclei in a neutron star environment could provide an extra coherent neutrino scattering. This behavior could be considered as an another crucial process, adding new information to the suggested models on neutron star cooling rate. On the other hand, local events of fusion cascade leading to the production of hyper-heavy nuclei can lead to an energy release due to a minimization of surface energy, that, in turn may lead to an additional mechanism of x-ray bursts. Alternatively, due to the local density profile modification deeper within the neutron star, gravitational wave signals may result from a violation of rotational symmetry [31].

Acknowledgments

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