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# Multifragmentation reactions and properties of stellar matter at subnuclear densities

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We point out the similarity of thermodynamic conditions reached in nuclear multifragmentation and in supernova explosions. We show that a statistical approach previously applied for nuclear multifragmentation reactions can also be used to describe the electroneutral stellar matter. Then properties of hot unstable nuclei extracted from the analysis of multifragmentation data can be used to determine a realistic nuclear composition of hot supernova matter.

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A type II supernova explosion is one of the most spectacular events in astrophysics, with huge energy releases of about $10^{53}$ erg or several tens of MeV per nucleon [1]. When the core of a massive star collapses, it reaches densities several times larger than the normal nuclear density $\rho_0 = 0.15\ \text{fm}^{-3}$. The repulsive nucleon-nucleon interaction gives rise to a bounce-off and creation of a shock wave propagating through the in-falling stellar material. This shock wave is responsible for the ejection of a star envelope that is observed as a supernova explosion. During the collapse and subsequent explosion, the temperatures $T \approx 0.5$–10 MeV and baryon densities $\rho \approx 10^{-5}$–$2\,\rho_0$ can be reached. As shown by many theoretical studies, a liquid-gas phase transition is expected in nuclear matter under these conditions. It is remarkable that similar conditions can be obtained in energetic nuclear collisions studied in terrestrial laboratories. This fact gives ground to the use of well-established models of nuclear reactions, after certain modifications, to describe matter states in the course of supernova explosions.

As demonstrated by several authors (see, e.g. [2,3]), present hydrodynamical simulations of the core collapse do not produce successful explosions, even when neutrino heating and convection effects are included. On the other hand, it is known that nuclear composition is extremely important for understanding the physics of supernova explosions. In particular, the weak reaction rates and energy spectra of emitted neutrinos are very sensitive to the presence of heavy nuclei (see, e.g. [4–7]). This is also true for the equation of state (EOS) used in hydrodynamical simulations since the shock strength depends on the dissociation of heavy nuclei. A popular EOS presently used in supernova simulations was derived in Refs. [8,9]. However, it is based on the properties of cold or nearly cold nuclei ($T < 1-2$ MeV) extracted from nuclear reactions at low (solid state target) density (i.e., $\rho \sim 10^{-14}\,\rho_0$). On the other hand, the properties of nuclei may change significantly at the high temperatures and baryon and lepton densities associated with supernova explosions. For a more realistic description of supernova physics, one should certainly use the experience accumulated in recent years by studying intermediate-energy nuclear reactions, in particular, multifragmentation reactions. We believe that properties of equilibrated transient systems produced in these reactions are similar to those expected in supernova explosions. Another shortcoming of the model [8,9] is that it reduces an ensemble of hot heavy nuclei to a single "average nucleus." This is an approximation, that may strongly distort the true statistical ensemble, and, at best, it can be applied only in a limited number of cases. Therefore, an urgent task now is to derive a more realistic EOS of hot and dense stellar matter that can be applied to a broad range of thermodynamic conditions. We took the first step in this direction in our previous paper [10]. Our goal in this paper is two-fold: First, we demonstrate that nuclear multifragmentation reactions reveal valuable information about properties of nuclei in dense surroundings, which is important for making reliable calculations of nuclear composition under astrophysical conditions. Second, we show that in a realistic approach one should consider the whole ensemble of hot neutron-rich nuclei and study how this ensemble evolves with temperature, density, and electron fraction in supernova matter.

In the supernova environment, as compared to nuclear reactions, new important ingredients occur. The matter at stellar scales is electrically neutral; therefore, electrons must be included to balance a positive nuclear charge. Energetic photons are also present in hot matter, and they can change the nuclear composition via photonuclear reactions. Finally, the flavor content of matter can be affected by a strong neutrino flux from the newlyborn protoneutron star. The crucial question for theoretical description is what degree of equilibration is reached in different reactions. Our estimates show that at the temperatures and densities of interest, the characteristic reaction times for nuclear interactions range from 10 to $10^6$ fm/$c$, which is very short compared to the characteristic time of the explosion (about 100 ms [2]). The assumption of nuclear equilibration is fully justified for these conditions, and therefore the nuclear composition can be determined from a statistical model. The rate of photonuclear reactions depends strongly on the density; and at very low densities, less than $10^{-5}$–$10^{-6}\,\rho_0$, these reactions are more efficient than nuclear interactions. The weak interactions are much slower. It is most likely that at high densities, $\rho \geqslant 10^{-3}\,\rho_0$, neutrinos are trapped in a nascent neutron star; but at lower densities, they stream freely from the star. The weak processes are entirely responsible for the neutrino and electron content of the matter. For example, the electron capture may not be in equilibrium with nuclear reactions at small densities [11]. Therefore, an adequate treatment is needed to discriminate various conditions with respect to the weak reactions [10]. We conclude that the statistical approach can be applied for nuclear reactions, but possible deviations from equilibration for weak and electromagnetic interactions should be explicitly taken into account.

Statistical models are very successful in nuclear physics if an equilibrated source can be defined in the reaction. For example, such a source is the "compound nucleus" introduced by Niels Bohr. The standard compound nucleus picture is valid only at low excitation energies when evaporation of light particles and fission are the dominating decay channels. However, this concept cannot be applied at high excitation energies, $E^* > 2$–3 MeV/nucleon, when the nucleus breaks up fast into many fragments. Several versions of the statistical approach have been proposed for the description of such multifragmentation reactions (see review [12]). As was demonstrated in many experiments (see, e.g. [13–17]), an equilibrated source can be formed in this case too, and statistical models are generally very successful in describing its properties. Systematic studies of such highly excited systems have revealed manifestations of the nuclear liquid-gas phase transition [18,19].

Presently, the statistical multifragmentation model (SMM) is the only model of multifragmentation that can be applied both for finite systems and in the thermodynamical limit for infinite systems [12,20]. This makes it possible to use it for astrophysical conditions. The model assumes nuclear statistical equilibrium at a low-density freeze-out stage. Light nuclei with mass number $A \leqslant 4$ are treated as elementary particles with only translational degrees of freedom (nuclear gas). Nuclei with $A > 4$ are treated as heated liquid drops. In this way, one may study the nuclear liquid-gas coexistence in the freeze-out volume. The Coulomb interaction of fragments is described within the Wigner-Seitz approximation. Different channels $f$ are generated by Monte Carlo sampling according to their statistical weights, $\propto \exp S_f$, where $S_f$ is the entropy of channel $f$. After the breakup, the Coulomb acceleration and the secondary deexcitation of primary hot fragments are taken into account.

An important advantage of the SMM is that it includes all breakup channels ranging from the compound nucleus to vaporization (channels containing only light particles $A \leqslant 4$), and one can study the competition between them. As shown already in Refs. [12,21], multifragmentation dominates over the compound nucleus at high excitation energies, and must be taken into account to explain multiple fragment production. This is demonstrated in Fig. 1 where, besides the total entropy, we show entropies of two extreme disintegration modes of $^{238}$U, namely the compound nucleus (CN) and the vaporization (V) channels, as functions of excitation energy. One can clearly see that the CN channel dominates at low excitation energies, but the V channel wins at excitation energies above 12 MeV/nucleon. However, in fact the CN channel dies out at much lower excitation energies, 2–3 MeV/nucleon, when the channels containing a heavy residue and/or several intermediate-mass fragments ($4 < A < 50$) have a higher entropy.

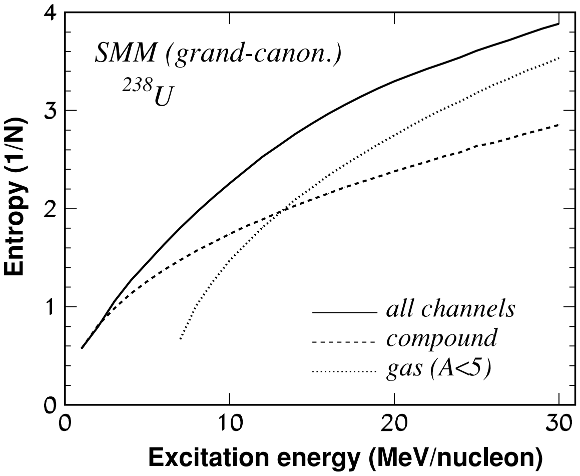

FIG. 1. Entropy per nucleon for different disintegration channels of $^{238}$U as a function of excitation energy per nucleon. Calculations are performed within the grand-canonical version of the SMM [12,21] at the freeze-out density $\rho = \rho_0/3$. Dashed and dotted lines correspond to compound nucleus and vaporization ($A \leqslant 4$) channels, respectively. Solid line is the total entropy, obtained by summing over all breakup channels.

We emphasize that the difference between the solid and dotted lines in Fig. 1 is caused entirely by the presence of hot heavy and intermediate-mass fragments. One can conclude that their contribution remains significant even at very high excitation energies and nuclear entropies up to 4 units per baryon. This result is relevant to the physics of supernova explosions since the survival of relatively heavy nuclei reduces energy losses for dissociation, and it may help revive the shock wave.

For astrophysical applications, it is important that the SMM, besides fragment partitions, can describe well the neutron content of fragments [13]. In the case of neutron-rich sources, the SMM predicts neutron-rich hot primary fragments. As calculations show [22,23], they keep a part of their neutron excess even after deexcitation. New experiments give evidence for the production of such unusual neutron-rich nuclei, which should be quite common for supernova matter. For example, Fig. 2 shows the neutron-to-proton ratio $(N/Z)$ for fragments produced in fragmentation of $^{238}$U with energy 1 GeV/nucleon on Pb and Ti targets [24]. Fission and spallation fragments were excluded from the analysis in order to guarantee selection of multifragmentation-like events. One can see that the observed neutron content of fragments with $Z < 60$ is larger than expected from the standard EPAX parametrization, which is a result of spallation-like processes considered previously as the main mechanism for production of these fragments. Moreover, at $Z < 30$ it becomes larger than the neutron content of stable nuclei. In Fig. 2, we demonstrate that the SMM can quantitatively describe this trend by predicting at the same time primary hot fragments with very large $N/Z$.

With the help of multifragmentation experiments, one can determine the model parameters needed to best describe of neutron-rich hot nuclei, for example, their symmetry energy. As discussed, the symmetry energy for fragments is defined in SMM as $E^{\rm sym}_{A,Z} = \gamma(A-2Z)^2/A$, where $\gamma$ is a phenomenological parameter. In the case of cold fragments,

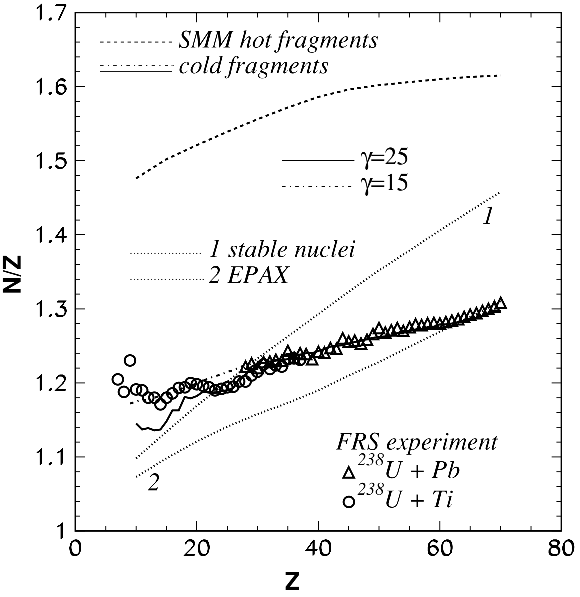

FIG. 2. Mean $N/Z$ vs charge of fragments produced in breakup of $^{238}$U with energy 1 GeV/nucleon on Pb and Ti targets. Points are experimental data obtained on fragment separator (FRS) at GSI [24]. Dashed line is SMM calculation for primary hot fragments; solid and dot-dashed lines are fragments after secondary deexcitation. Dotted line 1 corresponds to stable nuclei, dotted line 2 is the EPAX phenomenological parametrization for nuclei produced by spallation. Solid and dashed lines are calculations at the standard symmetry energy parameter $\gamma = 25$ MeV; dot-dashed line is for reduced $\gamma = 15$ MeV.

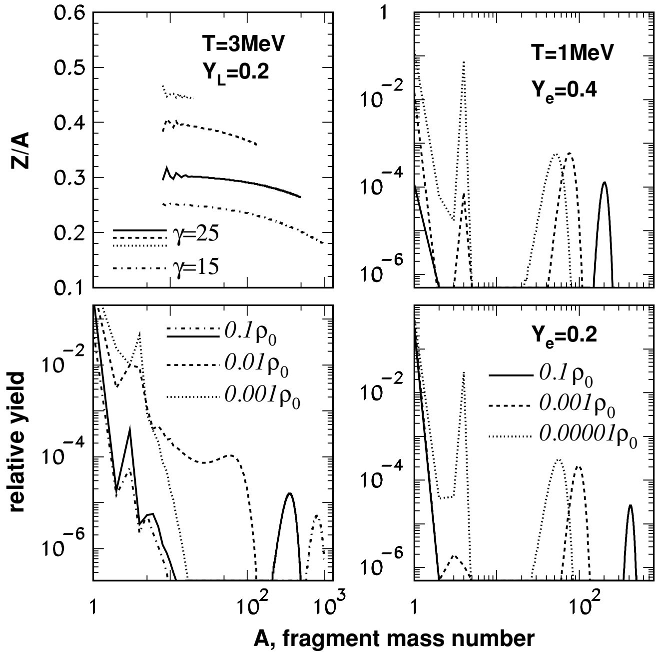

FIG. 3. Mean charge-to-mass ratios (left top panel), and mass distributions of hot primary fragments (other panels) calculated with the SMM generalized for supernova conditions. Left panels are calculations for temperature $T = 3$ MeV and fixed lepton fraction $Y_L = 0.2$ per nucleon. Right panels, for temperature $T = 1$ MeV and fixed electron fractions $Y_e$. Lines correspond to baryon densities shown in the figure. Solid, dashed, and dotted lines are calculations at the symmetry energy parameter $\gamma = 25$ MeV; dot-dashed lines are for reduced $\gamma = 15$ MeV.

$\gamma \approx 25$ MeV. For hot fragments, this parameter can be extracted, e.g., from the fits of isotope yields via the isoscaling phenomenon [25]. Presently, there are indications of the essential reduction of symmetry energy in hot nuclei [23,26]. A small discrepancy shown in Fig. 2 between the standard calculations with $\gamma = 25$ MeV and experiment for fragments with $Z < 20$ can be attributed to this effect: lower symmetry energy in the beginning of the secondary evaporation cascade can increase the neutron richness of final cold fragments [27]. This is demonstrated in Fig. 2 by SMM calculations with $\gamma = 15$ MeV (dot-dashed lines). The possibility of symmetry energy reduction should be kept open for the best description of hot nuclei produced at thermodynamical conditions close to those in multifragmentation reactions. Then these results can be used to find a realistic nuclear composition of supernova matter.

To describe supernova matter, we modified the SMM by including electrons and neutrinos in the statistical ensemble [10]. The model was formulated for different assumptions concerning weak reaction rates, which makes it flexible enough to be used for different stages of a supernova explosion. In Fig. 3, we present the SMM predictions for charge-to-mass ratios ($Z/A$) and mass distributions of hot nuclei for typical supernova conditions. We performed calculations for different temperatures and densities at fixed lepton (neutrinos+electrons) to baryon ($Y_L$), or electron to baryon ($Y_e$) fractions. One can see that at low temperatures ($T = 1$ MeV) the mass distributions have usually three peaks: at $A = 1$ (free nucleons), $A = 4$ ($\alpha$ particles), and a large $A \sim 100$ corresponding to heavy nuclei. This is a typical picture for a gas-liquid coexistence region. The distribution of heavy nuclei in this case can be well approximated by a Gaussian distribution. However, at higher temperatures ($T = 3$ MeV) the mass distributions can be very broad (see dashed line in the bottom left panel), and they become closer to a power law (for $A > 4$). As seen from the top left panel, the Z/A ratios vary from about 0.45 at low density to about 0.25 at higher densities.

We stress that a great variety of neutron-rich and even exotic (large mass, small charge) nuclei can be formed during the explosion. Our analysis [10] shows that decreasing the symmetry energy has a strong influence on the nuclear composition and favors formation of large neutron-rich nuclei. As an example, in Fig. 3 we demonstrate that masses and the $Z/A$ ratios of nuclei produced at standard $\gamma = 25$ MeV and at $\gamma = 15$ MeV are essentially different, by about a factor of 2, in the case of higher densities at $T = 3$ MeV. Another important effect in this case is that the isotope distributions at given $A$ (their widths are $\sigma_Z^A \approx \sqrt{(AT/8\gamma)}$, see [21,22]) become considerably broader. Therefore, properties of hot neutron-rich nuclei in supernova environments should be reconsidered in accordance with most recent laboratory experiments, in particular, regarding the symmetry energy.

Besides a more realistic EOS, there are other important aspects of supernova dynamics which are sensitive to the ensemble of hot nuclei. In particular, the neutrino opacity [7] and the electron capture rate [11] are very sensitive to the nuclear structure effects and to the symmetry energy. It is very promising to investigate consequences of new shells at very large neutron excess and the possible production of heavy, or even superheavy, nuclei under supernova conditions. The nucleosynthesis in supernova environments may also proceed differently if the ensemble of hot nuclei will provide new "seeds" for the $r$ process [28].

In conclusion, in this paper we have pointed out a similarity of nuclear matter states reached in multifragmentation reactions and in supernova explosions. As it is becoming clear from recent experiments, properties of nuclei produced in hot matter at subnuclear densities are essentially different from those for isolated nuclei at low excitation energies which were investigated by the nuclear structure community. The multifragmentation reaction allows us to investigate nuclei in the phase diagram region with $T \sim 3-8$ MeV and densities around $\rho \sim 0.1\,\rho_0$. It is complementary to the previous studies of isolated nuclei existing in matter with terrestrial densities and at small $T < 1-2$ MeV. The experimental information on properties of hot nuclei in dense surroundings is crucial for the construction of a reliable equation of state of stellar matter, since it allows for more reliable theoretical extrapolation to experimentally inaccessible regions. The improved EOS should be implemented into modern hydrodynamical simulations of supernova dynamics [2]. In this way, it will be possible to perform more realistic calculations of supernova explosions and synthesis of heavy elements.

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