Light Neutral Clusters in Supernova Matter

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Abstract—The role of weakly bound neutral clusters, such as dineutrons and tetraneutrons, in matter of high density and high temperature is discussed. Under such conditions, which are characteristic of core-collapse supernovae, the lifetime of multineutrons may prove to be sufficiently long for them to have a pronounced effect on the formation of the chemical composition. The influence of the multineutron binding energy and other nuclear properties on the magnitude of the effect being considered is examined.

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1. INTRODUCTION

A possible involvement of light neutron-rich nuclei (clusters) in astrophysical processes was considered by various authors (see, for example, [1, 2]). An unexpectedly high concentration of light clusters, such as \(^{4}\)He and \(^{8}\)He, in the central part of collapsing stars was recently revealed in [3]. These results were recently confirmed in [4]. In the present study, attention is given primarily to the possible role of dineutrons and tetraneutrons under conditions of high temperature and a high density, as well as under the conditions of a significant neutronization of matter, these conditions being characteristic of supernovae.

The dineutron and tetraneutron are possible quasibound states of several neutrons [5]. A short-term weakly bound state (of binding energy about 70 keV) of two neutrons (dineutron) may arise owing to the interaction of neutron magnetic moments, for example, in the \((T, p)\) reaction where the participant triton transfers two its neutrons to the target nucleus or in other reactions involving tritium or deuterium: \((T, T)\), \((D, T)\), or \((D, n)\). The dineutron lifetime is about a nuclear lifetime; in all probability [6], the dineutron may exist as a resonance or as a weakly bound system within the range of nuclear forces: in the neutron halo of highly neutron-rich nuclei [6–10] or in the neutron-star crust. In some studies, it is indicated that, in the beta decay of highly neutron-rich nuclei, where the emission of several neutrons is energetically favorable, two neutrons may be emitted not only sequentially but also in the form of a dineutron cluster [11]. Two neutrons may also be bound in a neutron halo of light nuclei [7].

For the first time, experiment devoted to searches for dineutrons were performed in 1948 [12, 13]. The first estimations of the dineutron binding energy were performed at the same time, \(Q_{2n} \approx 0.7 \pm 0.2\) MeV, and the dineutron lifetime with respect to beta decay was also assessed. Experiments aimed at dineutron searches were performed with the aid of various reactions involving the fusion of light nuclei [14–18] and the decay of heavy nuclei [19]. For example, Spyrou and his coauthors [20] reported on the detection of a dineutron in the decay of a \(^{16}\)Be nucleus (in its decay, the emission of one neutron is impossible) on the basis of recording two delayed neutrons emitted at a small angle.

In addition to dineutrons and tetraneutrons (see [5, 21–23] and references therein), other possible weakly bound multineutron states are also discussed in the literature [19, 23–25]. There is presently no unambiguous answer to the question of whether a tetraneutron exists in the form of a resonance or a bound state. Nowadays, experiments are being performed with the aim of observing a tetraneutron in predominantly three reactions: (i) the induced fission of \(^{238}\)U [26], (ii) the breakup of \(^{14}\)Be to \(^{10}\)Be and \(^{4}\)n [27] (this experiment was confirmed by calculations reported in [28, 29]), and (iii) the reaction \(^{4}\)He\(^{(6}\)He, \(^{8}\)Be)\(^{4}\)n [30]. However, theoretical calculations on the basis of modern models of two- and three-nucleon interaction do not provide an unambiguous proof of the existence of the tetraneutron [28]. If the experimental results obtained in [27, 30] are confirmed together with the arguments presented in [19, 31] in support of the existence of neutral clusters containing not less than six neutrons,
this would require revising modern theoretical models of nuclear forces [32].

The foregoing brings about the question of when and where these weakly bound states may manifest themselves. Under various conditions, reactions involving a dineutron (as well as other neutral clusters) may have a substantial effect on the results of nucleosynthesis (from primordial to equilibrium nucleosynthesis), changing the yield of product nuclides: $2n(p, n)D$, $D(2n, n)T$, $^3\text{He}(2n, n)^4\text{He}$, $^3\text{He}(2n, D)T$, and $^7\text{Be}(2n, n)^2\text{He}$. From an analysis of reactions with a dineutron in primordial nucleosynthesis, it was found [2] that, even if variations in fundamental constants (for example, in the pion mass) led to a change in the dineutron binding energy, this energy did not exceed 2.5 MeV within the first minutes after the Big Bang. Otherwise, the observed abundances of helium and deuterium in the Universe would be different.

In the present article, we will describe the equation of state for matter (Section 2) and consider the role of neutron clusters in the formation of the chemical composition of dense and hot supernova stellar matter (Section 3). We will also discuss those parameters on which the possible effect of a multineutron may be especially strong (Section 4). In addition, we will determine the dependence of the results on the binding energy of the multineutrons being considered (Section 5).

2. EQUATION OF STATE FOR MATTER

In order to calculate the properties and chemical composition of supernova matter, we will use two equations of state that were described in detail in [33, 34]. Both are based on the use of the approximation of nuclear statistical equilibrium, which is valid at temperatures that satisfy the condition $T \gtrsim 3 \times 10^9$ K. Under these conditions, all direct and inverse nuclear reactions are in equilibrium, in which case the chemical potential of an arbitrary nucleus with mass number $A$ and charge number $Z$ is straightforwardly expressed in terms of the neutron, $\mu_n$, and proton, $\mu_p$, chemical potentials as

$$\mu_{A,Z} = (A-Z)\mu_n + Z\mu_p.$$  \hspace{1cm} (1)

In the equation of state proposed by Nadyozhin and Yudin [33] (EoS NY in the following), nuclei are treated as a perfect Boltzmann gas, while neutrons and protons are assumed to have a form of a Fermi gas whose degree of degeneracy is arbitrary. For nuclei, one takes into account explicitly low-lying levels known from experiments and highly excited states through the Fermi gas model. In our calculations, we include about 400 nuclei—predominantly the nuclei of the iron peak and nuclei of light elements.

The equation of state proposed by Blinnikov, Panov, Rudzsky and Sumiyoshi [34] (EoS BPRS in the following) takes additionally into account matter nonideality effects: Coulomb interaction and interaction of nuclei with surrounding free nucleons. The latter is especially important at high densities. The partition functions for nuclei (without allowance for excited levels) are calculated according to [35]. In all, about 4500 nuclei were explicitly included in our calculation.

It should specially be noted that highly neutron-rich hydrogen and helium isotopes, which, as was found in [3, 4], may be abundant at high densities and temperature characteristic of core-collapse supernovae, were not included in the calculations in the aforementioned equations of state. This was done deliberately in order to demonstrate the effect of multineutrons against “standard” sets of nuclei.

In order to find the equilibrium chemical composition, it is necessary to solve the following set of equations for the component concentrations $n_i$:

$$\begin{aligned}
\sum_i n_i A_i &= n_b, \\
\sum_i n_i Z_i &= n_e.
\end{aligned} \hspace{1cm} (2)$$

Here, summation is performed over all nuclei (including free nucleons), while $A_i$ and $Z_i$ are, respectively, the mass and charge numbers of specific nuclei. Further, $n_b \equiv \rho/m_n$ is the baryon concentration ($\rho$ is the matter density, and $m_n$ is an atomic mass unit). Thus, the first equation in the set of Eqs. (2) is the condition of baryon-number conservation. In the second equation in the set of Eqs. (2), $n_e$ is the electron concentration; therefore, the second equation is the condition of electric neutrality of matter. It is convenient to define a dimensionless electron concentration (fraction) $Y_e$ as $Y_e \equiv n_e/n_b$. In matter featuring equal numbers of neutrons and protons (helium, $^4$He; carbon, $^{12}$C; etc.), $Y_e = \frac{1}{2}$; for iron, $^{56}$Fe, we have $Y_e = \frac{28}{56}$. We now fix the values of the temperature $T$, density $\rho$, and electron fraction $Y_e$. We can then solve the set of Eqs. (2) with respect to two variables, $\mu_n$ and $\mu_p$.

Substituting them into Eqs. (1), we find the chemical potentials and, hence, the concentrations of all other components. This solves the problem of determining the chemical composition of matter. Thus, the equation of state under conditions of nuclear statistical equilibrium is fully determined by specifying three parameters: $T$, $\rho$, and $Y_e$.

3. “STANDARD” CALCULATION OF CONCENTRATIONS

An example of the results obtained from calculations according to EoS NY with a standard set of
nuclei is given in Fig. 1. For the purposes of illustration, we chose the moment of time at which the matter density at the center of the collapsing stellar core reached a value of about \( \rho \approx 3 \times 10^{13} \text{ g cm}^{-3} \), in which case a time of about 1 ms remains before an moment of time of collapse termination (bounce effect). We choose this moment of time of the collapse process and the respective profiles of the distribution of thermodynamic parameters in the stellar core (for details of the calculation, see [36]) as a characteristic example that makes it possible to examine all special features of the distribution of the chemical composition of matter. At high densities, a substantial deviation from the ideality of matter arises because of a strong nuclear interaction between its components, and the equations of state that we consider become inaccurate. At a density of \( \rho \approx 10^{14} \text{ g cm}^{-3} \), nuclei disappear via a phase transition to uniform nuclear matter. Concurrently, the stiffness of the equation of state increases substantially, the rate of the collapse process at the center of the star being considered sharply becomes lower, and there arises a diverging shock wave leading eventually to the ejection of the stellar envelope—that is, to a supernova explosion.

Figures 1a, 1b, and 1c show the distributions of, respectively, the temperature \( T \) (in MeV units—1 MeV approximately corresponds to \( 1.16 \times 10^9 \text{ K} \)); logarithm of the density (in g cm\(^{-3}\)) units), \( \log \rho \); and the electron fraction \( Y_e \) in matter versus the mass coordinate \( m \) (in 10\(^{12}\) units, \( m = 0 \) corresponds to the center of the star). Figure 1d shows the chemical composition of matter (\( X \) is the weight fraction of an element) at the same moment of time. In just the same way as for electrons, the dimensionless concentrations are defined as the ratio \( Y_i \equiv n_i/n_b \), where \( n_i \) is the concentration of the \( i \)th element. For an element of mass number \( A_i \), the weight fraction \( X_i \) is naturally related to its concentration by the equation \( X_i = Y_i A_i \). The dash-dotted line marked by the symbol \( X_{Z>2} \) represents the total weight fraction of all nuclei for which \( Z_i > 2 \). As follows from the first equation in the set of Eqs. (2), the weight fractions \( X_i \)
satisfy the normalization condition $\sum_i X_i = 1$, where the sum is taken over all nuclei and free nucleons.

At large values of the coordinate $m$, one can see remnants of the original iron core of the star. The growth of the density and temperature as we move to the center leads to the dissociation of iron-peak nuclei to ever lighter elements, nucleons, and alpha particles. In addition, matter simultaneously undergoes a substantial neutronization (this corresponds to a decrease in $Y_e$ to a value of about 0.3 at the center) accompanied by the appearance of neutron-rich isotopes of chemical elements and an increase in their amount. The concentration of free neutrons also grows. It is noteworthy that, although isotopes of light elements have large individual concentrations (weight fractions) at the central part of the core, the total weight fraction of heavy elements (dash-dotted line) prevails there as well.

4. CALCULATION WITH ALLOWANCE FOR MULTINEUTRONS

Postponing, for the time being (see Section 6 below), the discussion on the validity of including unbound states of negative binding energy—dineutrons and tetraneutrons—in the calculation of the equation of state in the approximation of nuclear statistical equilibrium, we will take into account these neutral clusters in calculating the equation of state and examine the results obtained in this way. We will use zero value for the ground-state spin of either cluster and set the dineutron binding energy to $Q_{2n} = -66$ keV and the tetraneutron binding energy to $Q_{4n} = -0.8$ MeV [29].

Figure 2 illustrates a comparison of the results obtained for the equations of state being considered. Figures 2a and 2c refer to EoS NY, while Figs. 2b and 2d refer to EoS BPRS. The moment of time and conditions are identical to those in Fig. 1. Figures 2a and 2b show the distributions of weight fractions of $Z_i \leq 2$ light components of matter (in particular, the thick solid and dashed curves represent the contributions for dineutrons and tetraneutrons, respectively) in a central part of the core where $0 \leq m/M_\odot \leq 1$. In the outer part, the inclusion of multineutrons does not lead to any significant changes. One can see that, in the region of $m/M_\odot \lesssim 1$ (which, according to Fig. 1, corresponds to densities satisfying the condition $\rho \gtrsim 10^{11}$ g cm$^{-3}$), dineutrons are at least as abundant as other light nuclei; in the central part of the stellar core, they are even second to only free neutrons. As for tetraneutrons, they seem less significant, even though their contribution grows fast with increasing density. In principle, the two equations of state used, which are quite different, lead to a consistent picture in this respect, despite a difference in details.

We will now proceed to consider Figs. 2c and 2d. In them, the behavior of several summed EoS features calculated for the same region of the stellar core with a standard set of nuclei (thin curves) is compared with their counterpart for the extended set including multineutrons (thick curves). We recall that the number of nuclear species included in the calculations is strongly different for the two equations of state under consideration. We begin by examining a quantity with which we have already dealt in Fig. 1: the dash-dotted curve represents the total weight fraction of all $Z_i > 2$ “heavy” nuclei that was multiplied by a factor of 100 for convenience of a presentation. One can see that the inclusion of multineutrons leads to some decrease (of about 7% for EoS NY and about 5% for EoS BPRS) in the fraction of heavy nuclei. The symbols $A$ and $Z$ (solid and dashed curves) stand for their average mass number and average charge number, respectively. The averaging in question is performed according to the rule (see, for example, [37])

$$
\langle A \rangle \equiv \frac{\sum_{i} Z > 2 A_i n_i}{\sum_{i} Z > 2 n_i}, \quad \langle Z \rangle \equiv \frac{\sum_{i} Z > 2 Z_i n_i}{\sum_{i} Z > 2 n_i}.
$$

From these figures, it is also clear that the effect of multineutrons leads to some decrease (of about 5%) in the average charge and mass of heavy nuclei. Two points are in order here. First, the inclusion of multineutrons affects these quantities indirectly, since, in the two cases being considered (that is, the calculations with and without $2n$ and $4n$), averaging is performed over the same set of nuclei (those for which $Z_i > 2$). Second, a significant difference in the values of $\langle A \rangle$ and $\langle Z \rangle$ for the two equations of state being considered is noteworthy. For EoS NY, the average charge number in the central region is slightly greater than 10, while the average mass number is about 30, but, for Eos BPRS, $\langle Z \rangle \sim 40$, while $\langle A \rangle \gtrsim 100$. This is because EoS NY takes into account a very restricted region of nuclei that covers only $Z < 36$ and $A < 83$ nuclei. It follows that, here, the equilibrium chemical composition at high densities is a mixture of the iron-peak nuclei and nuclei of light neutron-rich elements. Not only is the region of nuclei considered in EoS BPRS wider by a factor of ten, but it also includes heavy neutron-rich nuclei, which prevail at high densities, leading to substantially greater values of $\langle A \rangle$ and $\langle Z \rangle$. Here, it is of importance that the two equations of state, which correspond to so different a basic chemical composition and to different underlying microscopic physics, make qualitatively similar predictions for the behavior of multineutrons in the region being considered.

The expression

$$
\sigma \equiv \sum_{i} Y_i A_i^2 = \sum_{i} X_i A_i,
$$

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Fig. 2. (a, b) Weight fractions $X_i$ of $Z \leq 2$ light elements and multineutrons (thick curves) versus the mass coordinate $m$ in the central region of the collapsing core at the same moment of time as in Fig. 1. The isotope symbols play the role of notation for the curves. (c, d) Various integrated EoS features, including the average values of the mass, $A$, and charge, $Z$, numbers; relative cross section for coherent neutrino scattering on nuclei, $\sigma$ (for more details, see main body of the text); and weight fraction of $Z > 2$ elements [both without $\gamma n$ and $\delta n$ (thin curves) and with allowance for them (thick curves)]. The results on display were obtained on the basis of (a, c) EoS NY and (b, d) EoS BPRS.

where summation is performed over all nuclei; free nucleons; and multineutrons, if any, is the last summed quantity whose behavior is depicted in Fig. 2 (dotted curve marked by the symbol $\sigma$). Particular attention to this quantity is motivated by the following argument: neutrinos play a dominant role in energy transfer during the process of collapse of the stellar core. It is intense flows of neutrinos of all flavors that carry away the overwhelming portion (about 99%) of the whole deposited energy. Therefore, the energy fraction associated with the ejection of the stellar envelope and with the photon flux, which is precisely what we observe as a supernova explosion is less than one percent. It turns out that, under the conditions being considered, coherent neutrino scattering on nuclei is one of the dominant processes of neutrino interaction with matter. Its cross section, $\sigma_{cs}$, is approximately in direct proportion to the square of the mass number of the nucleus involved: $\sigma_{cs}(A) \propto A^2$. It is the averaging of precisely this cross section over the chemical composition of matter that leads to the quantity $\sigma$ in Eq. (4). In contrast to the aforementioned average mass, $\langle A \rangle$, and charge, $\langle Z \rangle$, numbers of heavy nuclei, the parameter $\sigma$ additionally includes a direct contribution of multineutrons. One can see that a relative decrease in $\sigma$ is also moderately small, but, somewhere, it reaches 10%.

Summarizing the results obtained in this section, we can say that the $\gamma n$ and $\delta n$ effect on summed EoS features is relatively small, but, possibly, a consistent inclusion of other superheavy isotopes of light elements as well would lead to some noticeable changes in processes of neutrino production and propagation, if not in collapse dynamics, and may affect the chemical composition in the period after the bounce of the core.

5. SENSITIVITY TO PARAMETERS

Since exact values of multineutron parameters are unknown, it is of importance to study the sensitivity of our results to variations in their specific values—first of all, to variations in the binding energy. In order to do this, we have performed the
following calculation on the basis of EoS BPRS. For the specific thermodynamic-parameter values of $T = 4$ MeV, $\rho = 10^{13}$ g cm$^{-3}$, and $Y_e = 0.32$ (this approximately corresponds to the conditions in Fig. 1 at $m \approx 0.34$ $M_e$), we have calculated the chemical composition of matter at various values used for the $2n$ and $4n$ binding energies. The results are given in Fig. 3. The weight fractions of $Z \leq 2$ light nuclei and the total weight fraction of heavy nuclei, $X_{Z>2}$, are shown there versus the dineutron binding energy $Q_{2n}$ (Fig. 3a) and the tetraneutron binding energy $Q_{4n}$ (Fig. 3b). A negative binding energy naturally corresponds to an unbound state. We note, in passing that the experiment reported in [10] revealed a binding energy for light nuclei in excess of theoretical predictions. We varied the $2n$ binding energy over the range of $-1 \leq Q_{2n} \leq 1$ MeV and the $4n$ binding energy over the range of $-2 \leq Q_{4n} \leq 2$ MeV. The “commonly accepted” values of $Q_{2n} = -0.066$ MeV and $Q_{4n} = -0.8$ MeV are indicated by vertical dotted lines. The effect is seen to be quite moderate; it is the most pronounced for tetraneutrons. First of all, variations in the binding energies affect the multineutrons themselves, the concentrations of the other components remaining virtually unchanged. Thus, we can draw the conclusion that the calculated multineutron concentration is weakly sensitive to variations in the binding energies at preset values of the temperature and density. This comes as no surprise since only at high values of the density and temperature ($T = 4$ MeV in the example being considered) do multineutrons appear in matter. All thermodynamic quantities depend only on the ratio of the binding energy to temperature, $q \equiv Q/T$; in the region being considered, $|q| < 1$ is a small parameter, taking values in the vicinity of zero.

6. DISCUSSION

The explosion of a massive star as a supernova is initiated by the gravitational collapse of its core that underwent evolution. One possible explosion mechanism is based on energy transfer from a hot protoneutron star to a layer above its surface. This energy released from the core leads to the ejection of the envelope [38, 39]. The development of the explosion is accompanied by the deleptonization of protoneutron-star matter via neutrino emission over a time scale of about 10 to 30 s [40]. The emission of the bulk of neutrinos occurs at this stage, and it is of paramount importance to determine the spectrum of emitted neutrinos and their luminosity. An efflux of matter that forms a so-called hot wind occurs simultaneously during this explosion phase under the effect of neutrino-induced heating of the protoneutron-star surface in the deleptonization process [41]. Conditions for the development of nucleosynthesis of heavy elements produced under the effect of neutrons arise in this wind. Therefore, a correct calculation of neutrino transport is of crucial importance since this will make it possible to describe adequately the deleptonization process [42]. For this, one needs an adequate equation of state for matter.
and realistic reaction rates [43]. The importance of taking into account light clusters, such as deuterium and tritium, $^2\!\!\!\!\,^3\!\!\!\!\,^3\!\!\!\!\!^3\!\!\!\!\,^4\!\!\!\!\!^4\!\!\!\!\!^4\!\!\!\!\,\text{He}$; etc., in calculating the equation of state for matter has been discussed for a long time (see, for example, [44, 45] and references therein), but, to the best of our knowledge, no attention has thus far been given to the “exotic” possibility of taking into account multineutrons that was considered in the present article.

Let us now discuss known experimental data on multineutrons. The value that we use for the dineutron binding energy is negative ($Q_{2n} = -0.066$ MeV [5]). The requirement of agreement between the results of calculations and observations in simulating primordial nucleosynthesis in the Big Bang [2] sets an upper limit of 2.5 MeV on the dineutron binding energy. Moreover, investigations of elastic neutron scattering on deuterons, $(n, D)$, [46] give grounds to conclude that available data are incompatible with the existence of the dineutron whose binding energy is greater than 100 keV. According to a large number of studies [28, 30], the tetraneutron is likely to have a positive binding energy less than 3.1 MeV [27]; together with the dineutron, not only can the tetraneutron change the composition of matter during collapse, leading to a somewhat different input composition for the subsequent alpha process or r-process, but it is also able to affect the transparency of the neutrinosphere. Therefore, the ranges that we chose for values of the dineutron and tetraneutron binding energies (see Fig. 3) reflect their modern estimates.

In central regions of collapsing stellar cores, matter is under conditions of nuclear statistical equilibrium, in which case all direct and inverse reactions are in equilibrium. In addition, it is assumed that all possible states, including both bound states and states that have a resonance character and which lie in a continuum, should be taken into account in the calculation. A multineutron lifetime in the range of $10^{-12} - 10^{-21}$ s is likely to be sufficient for examining the possible involvement of these states in the determination of the properties of hot and dense astrophysical nuclear plasma. We will now discuss this point in more detail. We denote by $\tau$ the lifetime of the multineutron. Its decay rate is then $n_{mn}/\tau$, where $n_{mn}$ is its equilibrium concentration. A multineutron may originate, for example, from various collision-induced reactions; that is, its production rate is $n_i n_j (\sigma_v)$, where $n_{i,j}$ stands for the concentrations of colliding particles, $v$ is their relative velocity, and $\sigma$ is the cross section for the respective process. There are many such reactions, and each makes an individual contribution to multineutron production. For the sake of simplicity, we disregard similar reactions leading to multineutron disintegration, thereby obtaining an upper limit on the abundance of multineutrons. For characteristic values of thermodynamic parameters in the region of our interest (see Fig. 1), we take $T \simeq 5$ MeV and $\rho \simeq 10^{13}$ g cm$^{-3}$. The velocity is $v \simeq \sqrt{kT/m_n}$. From the balance of reactions, we can then obtain an order-of-magnitude estimate of the mass fraction of multineutrons in equilibrium. The result is

$$X_{mn} \simeq 10^{22} \cdot \tau(s) \rho_{13}\sqrt{T_5}\sum_{i,j} Y_i Y_j \sigma_b(i,j), \quad (5)$$

where $\rho_{13} \equiv \rho \times 10^{-13}$, $T_5 \equiv kT/5$ MeV, and the cross sections $\sigma_b$ are measured in barns. The sum in (5) is taken over all multineutron-production channels. The above estimates of lifetimes are compatible (depending on cross-section and lifetime values) with the significant multineutron contribution to the chemical composition of supernova matter under the conditions being considered.

We have shown that plasmas of supernova matter at high densities and temperature and under conditions of strong neutronization of matter may receive a significant contribution not only from neutron-rich hydrogen and helium isotopes [3, 4] (which we have not included in the present calculation) but also from light purely neutron clusters, the more so as multineutrons can contribute to the chemical composition of supernova matter under the conditions being considered.

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