R-process nucleosynthesis during explosion of low-mass neutron stars in close binaries

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ABSTRACT

We investigate the explosion of low-mass neutron stars through Newtonian hydrodynamic simulations. We couple the hydrodynamics to a nuclear reaction network consisting of ~ 4500 isotopes to study the impact of nuclear reactions, mainly neutron capture, $\beta$-decays, and spontaneous fission of nuclei, on the development of hydrodynamic instability of a neutron star. We show that after mass removal from the surfaces, low-mass neutron stars undergo delayed explosion, and an electron anti-neutrino burst with a peak luminosity of $\sim 3 \times 10^{50}$ erg s$^{-1}$ is emitted, while the ejecta is heated to $\sim 10^9$ K. A robust r-process nucleosynthesis is realized in the ejecta. Lanthanides and heavy elements near the second and third r-process peaks are synthesized as end products of nucleosynthesis, suggesting that the explosions of low-mass neutron stars could be a potentially important source of solar chemical elements.

Keywords: Neutron stars (1108) — Hydrodynamical simulations (767) — Neutrino astronomy (1100) — R-process (1324) — Solar abundances (1474)

1. INTRODUCTION

Neutron star binaries are intensively investigated for several decades both observationally and theoretically. The discovery of pulsar PSR B1913+16 in a neutron star binary by Hulse & Taylor (1975), and its orbital decay due to gravitational wave radiation (Weisberg et al. 1981) revealed the evolution of close neutron star binaries. The first ever multi-messenger detection of a binary neutron star merger in 2017 (Abbott et al. 2017; Goldstein et al. 2017; Savchenko et al. 2017) confirmed the encounter of neutron stars in close binaries. Apart from direct merger, Clark & Eardley (1977) discussed the mass transfer in a close neutron star binary with different initial masses. It was found that stable mass transfer can be established under certain circumstances, which would further enhance the asymmetry of the systems. Blinnikov et al. (1984) subsequently derived that such mass transfer caused by Roche lobe overflow is slow and stable until the mass of the lighter and larger neutron star reaches $\sim 0.15$ M$_\odot$. After that, tidal disruption of the low-mass neutron star occurs with a characteristic timescale longer than its hydrodynamic timescale, so it evolves through a series of quasi-equilibrium states until reaching the minimum stable mass $\sim 0.1$ M$_\odot$ allowed by the equation of state (EoS), and it explodes (Blinnikov et al. 1990; Blinnikov et al. 2021). A recent post-processing nucleosynthesis calculation by Panov & Yudin (2020) revealed the production of heavy elements through this event.

The nuclear reactions involved in the expansion of neutron star matter were examined by Lattimer et al. (1977). Simulations of low-mass neutron star explosions by Colpi et al. (1989, 1991, 1993) showed the essential roles of the nuclear reactions in the development of hydrodynamic instabilities. The timescale of weak interactions is considerably longer than the hydrodynamic timescale, and thus $\beta$-equilibrium cannot be always established dynamically when a neutron star is perturbed. The pressure of neutron star matter is not uniquely determined at a given density if the $\beta$-equilibrium is not achieved. Hence, the minimum mass of neutron stars determined from the EoS, in which the $\beta$-equilibrium condition is often assumed, does not necessarily correspond to the onset of instability. Hydrodynamic simulations of such a configuration with consideration of departure from $\beta$-equilibrium were performed. It was demonstrated that a sufficiently large ratio of mass removal, $\Delta S$, at the surface of the low-mass neutron star can lead to an instability. Sumiyoshi et al. (1998) further presented the explosion of the low-mass neutron star in a simulation with an initial mass removal ratio $\Delta S = 0.22$. An electron anti-neutrino burst with peak luminosity $\sim 10^{52}$ erg s$^{-1}$ was predicted. Moreover, r-process was realized in the expanding neutron star matter when its density drops rapidly, and rare-earth elements were produced.

Despite the inspiring predictions of neutrino burst and nucleosynthesis, several modifications of the model used by Sumiyoshi et al. (1998) are necessary for a more rigorous investigation. In this article, we revisit the reactive-
hydrodynamic simulations of low-mass neutron star explosions with a more modern nuclear matter EoS. A nuclear reaction network, instead of the single nucleus approximation, is employed to compute the relevant nuclear reactions, including neutron capture, β-decay, and spontaneous fission, that are essential for nucleosynthesis. We predict the yield of stable elements produced through this event, and we show that lanthanides and heavy elements near the second and third r-process peaks are synthesized. Our results suggest that the explosions of low-mass neutron stars could be a potentially new class of astronomical r-process events in addition to other known heavy element production channels (e.g., Kajino et al. 2019; Kobayashi et al. 2020).

This paper is organized as follows: in Section 2, we present the computational setup of the hydrodynamic simulations coupled with the nuclear reaction network. In Section 3, we present the numerical results of the simulations and the nucleosynthesis calculations. We discuss and conclude the findings in Section 4.

2. METHODOLOGY

2.1. Initial configuration

We adopt the EoS by Schneider, Roberts, and Ott (SRO) (Schneider et al. 2017, 2019), computed using the NRAPR Skyrme parametrization (Steiner et al. 2005), an effective non-relativistic Skyrme type nuclear interaction model (Latimer & Douglas Swesty 1991), and nuclear statistical equilibrium (NSE) approximation at low densities and temperatures, available in CompOSE1, in our study. We construct the initial configuration of the low-mass neutron star with a uniform temperature $T = 10^8$ K under hydrostatic and β-equilibrium. A pure Newtonian gravity and spherical symmetry are assumed. The minimum mass neutron star has a central density of about $1.211 \times 10^{14}$ g cm$^{-3}$, a total mass $M$ of about 0.0896 $M_\odot$, and a radius $R$ of more than 250 km (see Figure 1). The general relativistic correction to the low-mass neutron star structure is negligible as its compactness $C = GM/R^2 \sim 5 \times 10^{-4}$ is very small. Three simulation models, labeled by LMNS-50, LMNS-45, and LMNS-40, are performed in our study, which differ in the fission fragment asymmetry assumed (see Section 2.3).

2.2. Hydrodynamic simulation

The set of Euler equations in the Lagrangian formalism, in spherical symmetry, are:

\[
\frac{\partial u}{\partial t} = -4\pi r^2 \frac{\partial (p + q)}{\partial m} - \frac{Gm}{r^2},
\]

\[
\frac{\partial r}{\partial t} = u,
\]

where $G$ is the gravitational constant. The baryon mass $m$ contained within the radius $r$ from the center of the neutron star is chosen to be the Lagrangian mass coordinates, with the outward radial direction from the center defined as the positive direction. $u$, $\rho$, $p$, and $\varepsilon$ are the radial velocity, baryon mass density, pressure, and specific internal energy density of the fluid, respectively, as functions of time $t$ and $m$. A standard first-order Lagrangian finite-difference scheme (Richtmyer et al. 1967) with uniform mass grid is employed to solve the Euler equations numerically with the introduction of an artificial viscosity term $q$ whenever compression occurs, where $l = 2$ is the artificial viscosity coefficient having the dimensions of a length. In Equation (4), $\dot{\varepsilon}_{\text{nuc}}$, $\dot{\varepsilon}_\beta$, $\dot{\varepsilon}_\nu$, $\dot{\varepsilon}_f$, and $\dot{\varepsilon}_{\nu, \text{th}}$ denote the extra heating/cooling rates of the mass elements associated with thermonuclear reactions, β-decays, β-delayed neutrino emissions, spontaneous fission, and thermal neutrino emissions, respectively (see Section 2.3). Explicit first-order time discretization subjected to the Courant–Friedrichs–Lewy condition are chosen to update these hydrodynamic variables.

![Figure 1. Initial configuration of the low-mass neutron star at hydrostatic and β-equilibrium for the EoS by Schneider, Roberts, and Ott (SRO) (Schneider et al. 2017, 2019) at uniform temperature $T = 10^8$ K. The density (solid line) and electron fraction (dashed line) are plotted versus the radial coordinates in logarithm scale.](https://compose.obspm.fr)
2.3. Nuclear reaction network

We implement and adopt the open-source code for nuclear reaction network computation developed by Timmes et al. (2000). A network consisting of ~ 4500 isotopes (see Figure 2) is chosen to study the nucleosynthesis in this work. The atomic number \( Z \) of the isotopes included in the network ranging from \( Z_{\text{min}} = 0 \) for neutron to \( Z_{\text{max}} = 92 \) for uranium. The stable elements synthesized through standard r-process channels and their short-lived neutron-rich isotopes temporarily produced during the r-process are included. The nuclear masses, partition functions, and thermonuclear reaction rates of pair reactions with proton, neutron, \( \alpha \) particle, and photon, namely \((n, \gamma), (n, p), (p, \gamma), (\alpha, n), (\alpha, p), (\alpha, \gamma)\) processes, and their inverse processes, are adopted by Möller et al. (2003). Some special reactions, such as deuterium fusion and carbon burning, are implemented additionally. The thermal energy generation/absorption rate due to the thermonuclear reactions \( \dot{\epsilon}_{\text{nuc}} \) is computed by

\[
\dot{\epsilon}_{\text{nuc}} = -N_A \sum_i \frac{dY_i}{dt} M_i, \tag{6}
\]

where \( N_A \) is the Avogadro constant, \( Y_i \) is the number fraction and \( M_i \) is the nuclear mass of isotope \( i \). \( \sum \) is sum over all isotopes \( i \) in the network to find the net change in \( Y_i \) for all isotopes after the thermonuclear reactions.

The \( \beta \)-decay half-lives and \( \beta \)-delayed neutron emission probabilities of nuclei provided by Möller et al. (2003) are adopted. The energy available \( \Delta_j \) through the \( \beta \)-decay reaction \( j \) of an isotope with nuclear mass \( M(A, Z) \), where \( A \) denotes the mass number of the isotope, is given by

\[
\Delta_j = [M(A, Z) - M(A, Z + 1)] - \mu_e. \tag{7}
\]

The chemical potential of electron \( \mu_e \) enters the equation since the Fermi level of degenerate electron is high inside neutron stars. The endothermic \( \beta \)-decays are forbidden whenever \( \mu_e \) is higher than the energy released. The average energy carried away by each electron anti-neutrino \( \epsilon_{\nu_e} \) can be expressed as (Sumiyoshi et al. 1998)

\[
\epsilon_{\nu_e, j} = \frac{3}{7} \Delta_j^2 + 7\Delta_j \mu_e + 21 \mu_e^2 \tag{8}
\]

We take the approximation that the neutrinos produced through \( \beta \)-decays escape freely from the low-mass neutron star without any dissipation of energy (Meyer 1989). Hence, the thermal energy generation rate \( \dot{\epsilon}_B \) and the neutrino cooling rate \( \dot{\epsilon}_{\nu, B} \) with respect to \( \beta \)-decays are computed by

\[
\dot{\epsilon}_B = N_A \sum_j \frac{dY_j}{dt} \Delta_j, \tag{9}
\]

\[
\dot{\epsilon}_{\nu, B} = -N_A \sum_j \frac{dY_j}{dt} \epsilon_{\nu_e, j}, \tag{10}
\]

where summation over all \( \beta \)-decay reactions \( j \), with \( \Delta_j > 0 \) under the given \( \mu_e \), is performed. After the weak interactions, the heating effect owing to \( \beta \)-delayed neutron emissions is also calculated, which is found to be an insignificant contribution and is counted in \( \dot{\epsilon}_{\text{nuc}} \) for convention.

The spontaneous fission half-lives of heavy nuclei \( \tau_f \) (in unit of yr) with atomic number \( Z \geq 90 \) in the network are evaluated using the semi-empirical formula by Santhosh et al. (2010):

\[
\log_{10}(\tau_f) = a \left( \frac{Z^2}{A} \right) + b \left( \frac{Z^2}{A} \right)^2 + c \left( \frac{N - Z}{N + Z} \right) + d \left( \frac{N - Z}{N + Z} \right)^2 + e, \tag{10}
\]

where \( N \) is the neutron number of the nuclei, and \( a = -43.25203, b = 0.49192, c = 3674.3927, d = -9360.6, \) and \( e = 580.75058 \) are fitting parameters. We approximate the fission fragments after spontaneous fission by the equation

\[
N_i (A, Z) \rightarrow N_2 (\gamma A, \gamma Z) + N_3 [(1 - \gamma) A, (1 - \gamma) Z] \tag{11}
\]

when a nucleus \( N_i \) undergoes spontaneous fission to release two daughter nuclei, \( N_2 \) and \( N_3 \). The fission fragment asymmetry parameter \( \gamma \) controls the asymmetry of fission fragments. In the simulation models LMNS-50, LMNS-45, and LMNS-40, \( \gamma \) is set to be 0.50, 0.45, and 0.40, respectively. The model LMNS-50 executes symmetric fission fragment approximation, while the other two models roughly resemble the peaks of fission product yield distribution from more sophisticated fission fragment calculations (e.g., Hao et al. 2002). After calculating the change in \( Y_i \) of all isotopes \( i \) in the network caused by spontaneous fission, the thermal energy generation rate through spontaneous fission \( \dot{\epsilon}_f \) is computed by

\[
\dot{\epsilon}_f = -N_A \sum_i \frac{dY_i}{dt} M_i. \tag{12}
\]

The thermal neutrino energy loss rate \( \dot{\epsilon}_{\nu, \text{th}} \) through pair-, photo-, plasma-, bremsstrahlung and recombination neutrino processes are calculated using the open-source subroutine for thermal neutrino emission calculation\(^2\), which adopts the analytical fitting formulae by Itoh et al. (1996). It enters Equation (4) under the assumption that the thermal neutrinos escape freely from the neutron star. It is found that the cooling effect caused by thermal neutrino emission is negligible as the temperature reached by the exploding low-mass neutron star is not adequately high.

\(^2\)http://cococubed.asu.edu/
Figure 2. The isotopes included in the nuclear reaction network. The colored region covers the isotopes considered in the network, where the grids in red further illustrate the stable isotopes in the solar system (Lodders 2019). Extremely neutron-rich isotopes with proton number $Z > 80$ are not included because some of the nuclear reaction rates are not available to form linkages with other isotopes included.

2.4. Composition evolution

The chemical composition evolution of neutron star matter is computed individually for each mass element. The Maxwell-Boltzmann equation is solved under the given temperature, density, and electron fraction to assign the mass fractions of each isotope in the nuclear reaction network as the initial composition at NSE, which is shown in Figure 3. A threshold density $\rho_{th} \equiv 10^{13}$ g cm$^{-3}$ is defined. A mass element is regarded as core-like (crust-like) matter if its density is above (below) $\rho_{th}$. Above $\rho_{th}$, the neutron star matter are composed of predominantly free neutrons, with mass fraction $\geq 0.9$, and nuclei forming exotic nuclear structure, such as pasta-like configurations, immersed. The $\beta$-decay channels of nuclei are all blocked by the high electron chemical potential ($\mu_e \geq 30$ MeV, see Equation (7)). Consequently, we do not determine the composition of mass elements with a density exceeding $\rho_{th}$, and we neglect the nuclear reactions involved. The network is not activated for the mass elements composing of core-like matter in the hydrodynamic simulations.

The maximum temperature reached during the explosion of a low-mass neutron star is insufficient for efficient neutrino capture (Meyer et al. 1998) or positron capture (Ruffini et al. 2010) to contribute significantly to leptonization of the neutron star matter. The modified URCA processes are the major weak interactions between the free neutrons and protons, which are characterized by a timescale much longer than the relevant hydrodynamic timescale (Colpi et al. 1989). Hence, the $\beta$-decays of nuclei discussed in Section 2.3 are the only weak interactions that alter the electron fraction of the mass elements. Therefore, the electron fraction of mass elements regarded as core-like matter is fixed to the initial value obtained assuming $\beta$-equilibrium. When the density of a mass element drops below $\rho_{th}$, it transforms from core-like matter to crust-like matter. It is assumed that NSE is established after the transition from an exotic nuclear structure, such as pasta-like configurations, to a mixture of nuclei, free neutrons, and electrons as crust-like matter at that time step. The mass fractions of isotopes at NSE are assigned to be the composition of the mass element at the temperature, density, and electron fraction after the transition (see Figure 4). After that, the composition of the mass element evolves by solving the network coupled to the Euler equations.

The full network with all nuclear reactions considered is solved together with the Euler equations in order to investigate their effects precisely and consistently. It is believed that the leptonization owing to $\beta$-decays of nuclei and an overall net thermal energy generation by nuclear reactions enhance the expansion of the crust-like matter significantly. Hence, the leptonization and thermal energy generation are crucially responsible for the onset of hydrodynamical instability. The low-mass neutron star becomes unstable and explodes ultimately when it can no longer adjust itself against radial oscillations, and all mass elements are ejected. We perform the hydrodynamic simulation for $\sim 0.5$ s until the density of the mass elements drops near the minimum value available by the EoS table ($\sim 10^3$ g cm$^{-3}$). After that, we extrapolate$^3$ the density and temperature of the ejecta assuming homologous and adiabatic expansion described by $\rho(t) \propto t^{-3}$ and $T(t) \propto t^{-1}$ as functions of time $t$. We update the network for 1 Gyr after the hydrodynamic simulation to determine the stable elements produced by the explosion of the low-mass neutron star.

$^3$The extrapolation starts when the density of the mass elements reaches $\sim 10^4$ g cm$^{-3}$. To trace the evolution of all mass elements until the extrapolation can be started, we remove the outermost mass element whenever its density reaches near the minimum density available and continue the hydrodynamic simulation of the remaining mass elements up to $\sim 1$ s.
Figure 3. Initial mass fractions of isotopes at NSE for the neutron star crust-like matter. Ni62 and Fe56 are the major isotopes near the surface of the neutron star. The electron fraction decreases gradually as density increases and neutron-rich isotopes appear correspondingly. Free neutrons are dripped when the density is above \(4 \times 10^{11} \text{ g cm}^{-3}\), and become the predominate composition near the threshold density \(\rho_{\text{th}} \approx 10^{13} \text{ g cm}^{-3}\).

Figure 4. Mass fractions of isotopes at NSE and threshold density \(\rho_{\text{th}} \approx 10^{13} \text{ g cm}^{-3}\). The solutions at different temperature and electron fraction \(Y_e\) are shown. The mass fraction of free neutron is \(\approx 0.9\) (not shown in the figure) for the conditions concerned. For electron fraction between 0.016 and 0.030, the solutions at NSE are alike.

3. RESULTS

We have checked that the initial model of the low-mass neutron star constructed is stable in the hydrodynamic simulation coupled to the nuclear reaction network if no perturbation is imposed. To initiate an instability, we remove several mass elements from the surface of the star. We set \(\Delta S\), the ratio of mass removal to the total mass of the star, to be 0.40 to mimic the unstable mass transfer in the final approach of the binary system. The mass elements in between the 1st and 60th percentile in mass coordinates remain. Subsequently, a delayed explosion of the low-mass neutron star is observed.

3.1. Explosion of low-mass neutron star

The hydrodynamic simulation results of the model LMNS-50 are displayed in Figure 5. By imposing the initial mass removal, all the neutron star crust-like matter and part of the neutron star core-like matter are removed. The pressure gradient on the surface of the exposed core-like matter increases suddenly, and hydrostatic equilibrium is no longer maintained. The mass elements expand sequentially from the surface to the center. The perturbation made here, however, does not lead to a direct explosion of the whole configuration. Most of the mass elements oscillate and settle down at a larger radial position and a lower density temporarily at \(\approx 0.01\) s after the mass removal. The low-mass neutron star remains at quasi-equilibrium. If no nuclear reaction is included, the star oscillates around the new equilibrium position with most of the mass elements remaining gravitationally bound.

Meanwhile, the nuclear reaction network is activated since the densities of these mass elements are now lower than \(\rho_{\text{th}}\). The temperatures and electron fractions of the mass elements during the transition from core-like matter to crust-like matter are plotted in Figure 6. As discussed in Section 2.4, the NSE isotope abundances right after the transition are assigned. Note that the temperatures of some mass element are much lower than \(2 \times 10^4\) K, the typical minimum temperature that the NSE approximation is regarded as valid, during the transition. We assume that the NSE approximation still holds for these mass elements.

Figure 7 illustrates the evolution of the isotope abundance of a mass element in the 30th percentile in mass coordinates after the transition as an example. The difference between the assigned composition of the mass elements at different temperatures is eliminated by a robust r-process very soon. Therefore, the simulation results are not noticeably affected even if the NSE approximation may not be accurate at low temperature.

The r-process proceeds efficiently in all mass elements with evolutionary tracks analogous to the one displayed in Figure 7. The nuclear reactions increase the internal energy and electron fractions of these mass elements, which provide higher electron degeneracy pressure and thermal pressure. A net generation of thermal energy and increase in electron fraction
alter the hydrodynamic properties of the neutron star. The cumulative effects promote the expansion of mass elements, and the low-mass neutron star loses stability gradually. A delayed explosion of the whole configuration begins at $\sim 0.05$ s, with all mass elements becoming unbounded as ejecta. The radial velocity of the ejecta increases monotonically after the explosion due to the thermal energy generation and leptonization associated with the ongoing nuclear reactions. The total kinetic energy and the magnitude of the gravitational potential of the ejecta are $\sim 1.4 \times 10^{50}$ erg and $\sim 6 \times 10^{55}$ erg, respectively, at the end of the simulation.

Above the threshold density $\rho_{th}$ in our study, rearrangement of exotic nuclear structure occurs when the density of a mass element drops from $\sim 10^{14}$ g cm$^{-3}$ to $\sim 10^{13}$ g cm$^{-3}$ during the expansion. A rapid rise in temperature before 0.01 s is observed in Figure 5. As a result, the mass elements reach $\rho_{th}$ at different temperatures, as illustrated in Figure 6, owing to the properties of the exotic nuclear structure. We do not tackle with the effects of the exotic nuclear structure explicitly but focus on the nuclear reactions involved below $\rho_{th}$. After the network is activated, the mass elements are powered by the nuclear reactions. The high temperature up to $\sim 10^{10}$ K reached before the neutron star explodes is attributed to not only the heating effect by nuclear reactions, but also the adiabatic compression during radial oscillations. The exact peak temperature depends on the removed mass. We assume a large removal mass in this work, so that one single removal triggers directly the explosion. For a lower removed mass, the instability develops during pulsation, and the matter can develop an even higher temperature prior to explosion.

Figure 5. Radial positions (upper left panel), densities (lower left panel), temperatures (upper right panel), and velocities (lower right panel) of mass elements in the hydrodynamic simulation versus time. The radial positions and densities are plotted versus time in logarithm scale, while the temperatures and velocities are plotted versus time in linear scale. After the initial mass removal, the mass elements near the surface of the exposed neutron star core-like matter start expanding promptly. All mass elements gain outward radial velocity in the first $\sim 0.01$ s after the mass removal, though most of them remain gravitationally bound. They fall back onto the neutron star after $\sim 0.01$ s and undergo radial oscillation. A new equilibrium of the low-mass neutron star with lower central density is temporarily found between $\sim 0.01 - 0.05$ s. Nonetheless, the nuclear reaction network is activated as the density of the mass elements is lower than the threshold density $\rho_{th} \approx 10^{13}$ g cm$^{-3}$. The heating effect and leptonization caused by the nuclear reactions alter the structure of the neutron star in a quasi-equilibrium state. The star losses stability after $\sim 0.05$ s, leading to a delayed-explosion.
After the explosion at \( \sim 0.05 \) s, the nuclear reactions, mainly \( \beta \)-decays of nuclei, power the ejecta continuously. The temperature of the ejecta is sustained at \( \sim 10^9 \) K and decreases slowly because of adiabatic cooling. The net cumulative thermal energy deposited on the low-mass neutron star by the network is \( \sim 10^{50} \) erg within the hydrodynamic simulation time of the three models (see Figure 8). Electron anti-neutrino emission associated with \( \beta \)-decays of nuclei is predicted using Equation (8) during the explosion of a low-mass neutron star. The time evolution of electron anti-neutrino luminosity for the three models is shown in Figure 9. A peak luminosity of \( \sim 3 \times 10^{50} \) erg s\(^{-1}\) is reached shortly after the mass removal in the three models. The little trough in the luminosity at \( \sim 0.01 \) s is caused by the transient rise in electron chemical potential (see Equation (7)) associated with adiabatic compression during radial oscillations of the star. After the peak in neutrino emission, the average luminosity is maintained at \( \sim 10^{50} \) erg s\(^{-1}\) until the end of simulations at \( \sim 0.5 \) s.

3.2. Electromagnetic radiation and neutrino emission

From the nucleosynthesis calculations, we notice that the net thermal energy generation rate and neutrino luminosity are sustained until \( \sim 1.6 \) s and plunge when the mass fraction of free neutron vanishes (see Figure 10 for the evolution of relevant quantities of the mass element in the 30th percentile in mass coordinates as an example). The temperature of the ejecta remains high, and the expansion is continuously powered by the nuclear reactions until the free neutrons are exhausted and the production of neutron-rich nuclei with short \( \beta \)-decay half-lives is terminated. An electromagnetic peak near soft-gamma ray lasting for a few seconds in total is expected accordingly assuming black body emission. Likewise, the neutrino emission should last for a few seconds and diminishes rapidly following the termination of r-process.

The hydrodynamic evolution of the models LMNS-45 and LMNS-40 are very similar to that of LMNS-50. Also, the neutrino luminosities of the three models are similar in general. These results are insensitive to the variation in fission fragment asymmetry parameter \( \gamma \) discussed in Section 2.3.

We have also set the initial mass removal ratio \( \Delta S \) to be other values in between 0.36 and 0.40. With an even lower \( \Delta S \), the explosion is postponed and the pulsating phase extends substantially. It takes a very long time to do the simulation with even lower \( \Delta S \). After that, the star explodes in a similar way as illustrated in Figure 5.

3.3. Nucleosynthesis

During the explosion of a low-mass neutron star, the neutron star matter in the core, with initially very low electron fraction, is decompressed without experiencing strong heating. The maximum temperature reached by the mass elements in the simulation is \( \sim 10^{10} \) K, which is much lower than the typical temperature scale in other astronomical r-
process sites, such as core-collapse supernovae and binary neutron star mergers. A robust r-process occurs because of the initially high neutron excess and low electron fraction of the ejecta. Beyond the simulation time, we extend the nucleosynthesis calculations by extrapolating the density and temperature of the ejecta assuming free expansion. It is noticed that all mass elements experience similar evolutionary tracks of composition. The temperatures and electron fractions of three representative mass elements when the network starts operating are listed in Table 1. The inner ejecta, originating from the neutron star core region, has relatively high initial temperature and electron fraction after the decompression. The intermediate ejecta has moderate temperature and a low initial electron fraction. The outer ejecta, with almost no adiabatic compression during the radial oscillations, is initially cold and has moderate electron fraction.

The mass fractions of isotopes produced in the three selected mass elements from the three models LMNS-50, LMNS-45, and LMNS-40 after 1 Gyr are plotted versus mass number and atomic number in Figure 11–13. The solar abundance distribution by Lodders (2019), scaled to match with the production peak of Xe132 in the 10th mass element, is shown by the black scatters in the figures for comparison. With the occurrence of a robust and long-lasting r-process in all mass elements, the composition evolution becomes insensitive to the tiny difference among the initial conditions of these mass elements. The end products of nucleosynthesis in all mass elements from the same model are very similar.

On the other hand, the production curves of the three models are distinct because of the different fission fragment asymmetries. In the model LMNS-50, abundant production of elements near the third r-process peak ($A \approx 195$), comparable to the solar abundance observation, is found. Lanthanides ($Z = 57 - 71$) are insufficiently synthesized, especially for those before gadolinium ($Z = 64$). Due to the symmetric fission fragment approximation applied, elements with $Z < 45$ are not produced after spontaneous fission of heavy nuclei. The end products of nucleosynthesis are lacking in elements before the second r-process peak ($A \approx 130$). In the model LMNS-45, the solar abundance distribution is well recovered from the second r-process peak to the third r-process peak. Moreover, an excessive production of elements at the third r-process peak is obtained. As in the production curve of the model LMNS-40, elements slightly less massive than the second r-process peak are presented. However, elements slightly deviated from the second r-process peak are significantly under-produced when compared to the solar abun-
The thermal energy injected into the neutron star matter from the fission is rather minor in comparison. The net cumulative thermal energy generated through thermonuclear reactions and spontaneous fission is rather minor in comparison. The overall thermal energy generated through thermonuclear reactions and spontaneous fission is rather minor in comparison. The net cumulative thermal energy injected into the neutron star matter from the network is in the order of $10^{50}$ erg, which is only $\sim 0.1 - 1\%$ of its rest mass. While the nuclear energy is a negligible contribution of energy in other astronomical simulations of typical neutron stars, it plays a significant role in a low-mass neutron star, which is just marginally stable.

The peak luminosity of electron anti-neutrino emission due to $\beta$-decays of nuclei predicted by our models is 1-2 order lower than the values reported by Colpi et al. (1993) and Sumiyoshi et al. (1998). A maximized choice of the coefficient of $\beta$-decay rate estimation formula with uncertainty (Lattimer et al. 1977) used in their studies is responsible for the difference, where Sumiyoshi et al. (1998) has already pointed out that the $\beta$-decay rate is probably overestimated in their simulations. Adopting realistic $\beta$-decay half-lives of nuclei, our calculations predict a neutrino burst with lower peak in luminosity but lasting for a longer duration. The ejecta is powered by the nuclear reactions, and thus the temperature stays at $\sim 10^9$ K despite adiabatic cooling. At the end of simulation, the radius of the outermost mass element grows to $\sim 10^4$ km. Radiative cooling may become effective when the surface area of the expanding ejecta is large, and the temperature should decline more quickly. Further investigation is required to predict whether a soft-gamma ray burst, with high enough luminosity to be observed from the earth, is associated with the explosion of the low-mass neutron star. A bolometric light curve powered by the nuclear reactions may be obtained for further research.

The explosion of low-mass neutron star releases $\sim 0.05 M_\odot$ of ejecta in total. The r-process occurs in all mass elements according to our calculations. The excessive production of elements near the third r-process peak is observed, especially in the models LMNS-45 and LMNS-40. We attribute the synthesis of heavy elements of this event to the initially low electron fraction and the relatively low temperature of the ejecta. The two conditions allow the nucleosynthesis to operate under a high neutron excess environment for sufficiently long duration. A similar scenario is also realized in neutron star mergers with high neutron excess. The observation of lanthanides and elements at the third r-process peak associated with a binary neutron star merger by Tanvir et al. (2017) suggests the crucial contribution from neutron star ejecta to the heavy elements production in the universe. The neutron star merger as a promising astronomical r-process site is under extensive studies (e.g., Kullmann et al. 2022).

Meanwhile, several recent research on binary neutron star mergers and black hole-neutron star mergers suggested that cold dynamical ejecta, originating from the outer regions of neutron stars, may abundantly produce heavy elements up to the third r-process peak (e.g., Cowan et al. 2021). Our simulation results basically agree with the prediction that cold ejecta from neutron stars is favorable for the formation of elements near the third r-process peak (Korobkin et al. 2012). Furthermore, the recent investigation on the nucleosynthesis of low-mass neutron star explosion by Panov & Yudin (2020) found that heavy elements up to the third r-process peak can be excessively formed in the ejecta from the inner crust initially. We notice that such a feature is also present in our results regarding ejecta originating from deeper regions of the low-mass neutron star. While the nucleosynthesis calculation in their work is performed without coupling to the hydrodynamic, we may realize that the robustness of the r-process during the low-mass neutron star explosion is insensitive to the hydrodynamic evolution of the ejecta with sufficiently low initial electron fraction. The total dynamical ejecta mass

| percentile [th] | $T_i$ [GK] | $Y_{e,i}$ | ejecta category |
|-----------------|-----------|----------|----------------|
| 10              | 4.007     | 0.0261   | inner          |
| 30              | 3.777     | 0.0204   | intermediate   |
| 50              | 0.100     | 0.0233   | outer          |

Table 1. Percentile in mass coordinates, initial temperature $T_i$, and initial electron fraction $Y_{e,i}$ of the three chosen mass elements when the nuclear reaction network starts operation at the threshold density $\rho_{th} \equiv 10^{13}$ g cm$^{-3}$. All ejecta are classified into three categories, which are well represented by the three mass elements presented.
Figure 11. Mass fractions of isotopes versus mass number $A$ and atomic number $Z$ of the mass elements in 10th, 30th, and 50th percentile in mass coordinates at the end of nucleosynthesis calculation for the model LMNS-50. The solar abundance distribution (Lodders 2019) scaled to match with the mass fraction of Xe132 in the 10th mass element is shown by the black scatters.

Figure 12. Same as Figure 11, but for the model LMNS-45.

Figure 13. Same as Figure 11, but for the model LMNS-40.

from binary neutron star mergers are typically in the order of $10^{-3} - 10^{-2} M_\odot$ (Radice et al. 2018; Kasliwal et al. 2022), less than what we have obtained from low-mass neutron star explosions. Therefore, the latter should also contribute to the heavy element abundances if their event rate is comparable to that of binary neutron star mergers.

We demonstrate that the fission fragment calculation can significantly affect the nucleosynthesis results. The fragment asymmetry parameter $\gamma$ is introduced to mimic the fission fragment distribution. The study by Hao et al. (2022) revealed that the asymmetric fission fragment calculation schemes in the models LMNS-45 and LMNS-40 should result in more reliable results than those with symmetric fission fragment, such as in LMNS-50, as well as previous studies by Colpi et al. (1993) and Sumiyoshi et al. (1998). Further study may be conducted by determining the fission fragment distribution for each isotope individually using the method described by Hao et al. (2022), which should improve the accuracy of
the predicted heavy elements production. Moreover, neutron-induced, and $\beta$-delayed fission may be included. Nevertheless, the fission properties, as well as other nuclear reactions involving neutron-rich and heavy nuclei, are not well determined experimentally. Theoretical data must be used in r-process simulation studies, and thus systematic uncertainties always remain in these nucleosynthesis calculations, including the results presented in this paper.

A crucial assumption of our study is the existence of peculiarly light neutron stars with mass $\sim 0.1 M_\odot$ in close neutron star binaries. Even though such a configuration is allowed by modern EoS, neutron star with such a small mass has never been observed (Suwa et al. 2018). Nevertheless, recent research on asymmetric neutron star binaries (e.g., Vincent et al. 2020; Ferdman et al. 2020) open a door to the dynamical formation of low-mass neutron stars through mass transfer. In our study, a large fraction of mass ($\Delta S = 0.40$) is removed from the surface of the low-mass neutron star initially. Whether this treatment is realistic in describing the tidal stripping of the low-mass neutron star is unclear. We find that the delayed explosion of the low-mass neutron star is considerably postponed if the initial mass removal ratio $\Delta S$ is lower than 0.40. Although the hydrodynamic evolution of the star after losing stability is rather independent on the exact value of $\Delta S$, it experiences more periods of radial oscillation during the quasi-equilibrium state if $\Delta S$ is smaller. In addition, the temperature of the neutron star crust-like matter may temporarily exceed $10^{10}$ K whenever the compression wave arrives. Neutrino capture and positron capture may additionally give rise to leptonization beside $\beta$-decays of nuclei. Whether the electron fraction remains as low as the value found in our study has to be justified. On the other hand, a small value of $\Delta S$ may contradict with the conditions described by Clark & Eardley (1977) and Blinnikov et al. (1984) that the tidal disruption of the whole low-mass neutron star happens at most within the order of seconds. While the massive companion is assumed to be stable during the mass transfer in this paper, the influence by the massive companion must be considered if the instability of the low-mass neutron star takes a long duration to be developed.

A robust r-process nucleosynthesis is realized in the ejecta from the explosion of a low-mass neutron star. Lanthanides and heavy elements near the second and third r-process peaks are synthesized as end products of the nucleosynthesis.

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