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Nuclear equation of state for core-collapse supernova simulations with realistic nuclear forces

H. Togashi [a,b,*], K. Nakazato [c], Y. Takehara [d], S. Yamamuro [d], H. Suzuki [d], M. Takano [b,e]

[a] *Nishina Center for Accelerator-Based Science, Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

[b] *Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan*

[c] *Faculty of Arts and Science, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan*

[d] *Department of Physics, Faculty of Science and Technology, Tokyo University of Science, Yamazaki 2641, Noda, Chiba 278-8510, Japan*

[e] *Department of Pure and Applied Physics, Graduate School of Advanced Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku-ku, Tokyo 169-8555, Japan*

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Abstract

A new table of the nuclear equation of state (EOS) based on realistic nuclear potentials is constructed for core-collapse supernova numerical simulations. Adopting the EOS of uniform nuclear matter constructed by two of the present authors with the cluster variational method starting from the Argonne v18 and Urbana IX nuclear potentials, the Thomas–Fermi calculation is performed to obtain the minimized free energy of a Wigner–Seitz cell in non-uniform nuclear matter. As a preparation for the Thomas–Fermi calculation, the EOS of uniform nuclear matter is modified so as to remove the effects of deuteron cluster formation in uniform matter at low densities. Mixing of alpha particles is also taken into account following the procedure used by Shen et al. (1998, 2011). The critical densities with respect to the phase transition from non-uniform to uniform phase with the present EOS are slightly higher than those with the Shen EOS at small proton fractions. The critical temperature with respect to the liquid–gas phase transition decreases with the proton fraction in a more gradual manner than in the Shen EOS. Furthermore, the mass and proton numbers of nuclides appearing in non-uniform nuclear matter with small proton fractions are larger than those of the

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[*] Corresponding author at: Nishina Center for Accelerator-Based Science, Institute of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-0198, Japan.

E-mail address: hajime.togashi@riken.jp (H. Togashi).

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Shen EOS. These results are consequences of the fact that the density derivative coefficient of the symmetry energy of our EOS is smaller than that of the Shen EOS.

Keywords: Nuclear matter; Nuclear EOS; Variational method; Neutron stars; Supernovae

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1. Introduction

Core-collapse supernova explosions occur at the end of the evolution of massive stars heavier than 8 $M_\odot$. At the final stage of these stars, the stellar central core is composed of highly-degenerate electrons and heavy nuclides such as irons. Owing to photodisintegration of heavy nuclei and electron capture reactions, the core becomes gravitationally unstable, and begins to collapse. During the collapse, neutrinos created through the weak interaction are trapped in the core because they are scattered by other particles, mainly heavy nuclei. When the central density of the core approaches the nuclear saturation density, the core becomes stiffer and the resulting core bounce produces an outgoing shock wave. The shock wave stalls once as a result of the energy loss caused by the photodisintegration of in-falling heavy nuclei and neutrino emissions. According to the neutrino-heating mechanism, a convincing scenario for core-collapse supernovae [1], the stalled shock then revives as neutrinos emitted from inside the core react with matter through the weak interaction and deposit energies to matter behind the shock.

The above-described scenario of the core-collapse supernovae relies on two characteristics of nuclear matter: The stiffness of high-density nuclear matter, which causes a bounce of the core, and the species of nuclides in hot matter with which the neutrinos react. These two characters are given in the nuclear equation of state (EOS). In particular, because the stiffness of nuclear matter is governed by the repulsion of nuclear forces, it should be described with a nuclear Hamiltonian composed of realistic nuclear potentials. However, in the supernova EOSs proposed so far, the relation between bare nuclear forces and stiffness of nuclear matter is unclear as those EOSs are based on phenomenological nuclear models. The Lattimer–Swesty EOS [2], which is one of the standard supernova EOSs, is constructed with an effective Skyrme interaction, while the Shen EOS [3–5], which is another standard supernova EOS, is constructed based on the relativistic mean field (RMF) theory with the parameter set TM1 [6]. The Shen EOS was extended so as to take into account hyperon mixing [5,7] and quark–hadron phase transition [8]. While the symmetry energy of the Shen EOS (36.9 MeV) is rather larger than the empirical value [9], supernova EOSs based on RMF theories other than TM1 have also been proposed [10]. However, there is no supernova EOS based on bare nuclear forces yet.

The current status of supernova EOS studies motivated us to construct a new supernova EOS based on the variational many-body theory with realistic nuclear forces. In this research project, we employ the Argonne v18 (AV18) two-body nuclear potential [11], which reproduces the experimental two-nucleon scattering data and deuteron properties, and the Urbana IX (UIX) potential [12] for the three-body nuclear force. We then calculate the free energy per nucleon of uniform nuclear matter with the cluster variational method using the Jastrow wave function. Here we note that the thermodynamic quantities of asymmetric nuclear matter with arbitrary proton fractions are necessary to complete a supernova EOS table, while it is difficult to perform sophisticated variational calculations such as the Fermi Hypernetted Chain (FHNC) calculations for asymmetric nuclear matter. Therefore, we employ a simplified two-body cluster approxima-