Supernova equation of state based on realistic nuclear forces[†]

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The equation of state (EOS) for hot nuclear matter is one of the main ingredients in astrophysical simulations, such as core-collapse supernovae, cooling of protoneutron stars, black hole formations, and binary neutron star mergers. In order to describe the properties of nuclear matter in these simulations, a nuclear EOS table containing various thermodynamic quantities in wide ranges of the baryon number density $n_{\rm B}$, proton fraction $Y_{\rm p}$, and temperature T is necessary. Therefore, it is not an easy task to construct a nuclear EOS suitable for the astrophysical simulations. In fact, a limited number of nuclear EOSs are currently available for the core-collapse simulations.[1)] Furthermore, high-density uniform matter is treated with the phenomenological models in those EOSs. Under these circumstances, we have recently constructed a new nuclear EOS table based on realistic nuclear forces.[2)]

For uniform nuclear matter, the EOS is constructed with the cluster variational method. At zero temperature, we calculate the energy per nucleon as an expectation value of the realistic nuclear Hamiltonian composed of the Argonne v18 two-body and Urbana IX three-body potentials with the Jastrow wave function in the two-body cluster approximation. The obtained energies for pure neutron matter and symmetric nuclear matter are in good agreement with the results of the more sophisticated Fermi hypernetted chain (FHNC) variational calculations by Akmal *et al.*[3)] At finite temperature, the free energy per nucleon for uniform nuclear matter was calculated with an extension of the variational method by Schmidt and Pandharipande.[4)] The obtained results for pure neutron matter and symmetric nuclear matter are also in good agreement with those obtained using FHNC calculations.[5)]

For non-uniform nuclear matter, we adopt the Thomas-Fermi approximation following the method by Shen *et al.*[6)] In this method, non-uniform nuclear matter is assumed to be a mixture of free neutrons, free protons, alpha particles, and a single species of heavy nuclei that is located at the center of a Wigner-Seitz cell in a body-centered cubic lattice. We then calculate the free energy per nucleon for non-uniform matter by minimizing the average free energy density of the Wigner-Seitz cell with respect to the parameters specifying the density distributions of particles in the cell.

Table 1. Ranges of temperature T, proton fraction $Y_{\rm p}$, and baryon mass density $\rho_{\rm B}$ in the table of the variational EOS. At the top of the last column, "+1" represents the case at $T = 0$ MeV.

Parameter	Min	Max	Mesh	Number
$\log_{10}(T)$ [MeV]	-1.00	2.60	0.04	$91+1$
$Y_{\rm p}$	0	0.65	0.01	66
$\log_{10}(\rho_{\rm B})$ [g/cm^3]	5.1	16.0	0.1	110

Finally, we determine the thermodynamically favorable state for each $n_{\rm B}$, $Y_{\rm p}$, and T, by comparing the free energy for non-uniform nuclear matter with that for uniform nuclear matter. The obtained free energy and related thermodynamic quantities are tabulated in ranges of $n_{\rm B}$, $Y_{\rm p}$, and T, as shown in Table 1. Here, the baryon mass density $\rho_{\rm B}$ is defined as $\rho_{\rm B} = m_{\rm u} n_{\rm B}$ with $m_{\rm u}$ being the atomic mass unit.

The obtained EOS for various $n_{\rm B}$, $Y_{\rm p}$, and T is reasonable as compared with the Shen EOS.[6)] It is also found that the critical temperature with respect to the liquid–gas phase transition decreases more moderately with $Y_{\rm p}$ for our EOS. Furthermore, masses of heavy nuclides are slightly larger than those of the Shen EOS in neutron-rich nuclear matter. As reported in Refs. 2, 7), those results are caused by the fact that the density derivative coefficient of the symmetry energy L of our EOS is smaller than that of the Shen EOS.

To the best of our knowledge, this is the first nuclear EOS for astrophysical simulations based on realistic nuclear forces. In the near future, we will extend the present EOS so as to take into account the additional hyperon degrees of freedom at finite temperature, because the hyperon mixing is expected to strongly affect the EOS of dense matter at high densities. In fact, we have already calculated the EOS of hyperonic matter at zero temperature by using the cluster variational method.[8)]

The EOS table constructed in this study is open for general use in the studies of nuclear physics and astrophysics. The complete EOS table is available on the Web at `http://www.np.phys.waseda.ac.jp/EOS/`.

References

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