Variational approach to neutron star matter with hyperons

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We study the equation of state (EOS) for neutron star matter containing Λ and Σ^- hyperons by the cluster variational method using bare baryon interactions, as an extension of the EOS of nucleon matter we have constructed recently [1].

In Ref. [1], we constructed the EOS of uniform nucleon matter for arbitrary proton fractions at zero and finite temperatures by the cluster variational method starting from the realistic nuclear Hamiltonian composed of the Argonne v18 (AV18) two-body potential and Urbana IX (UIX) three-body potential. The obtained energies for symmetric nuclear matter and pure neutron matter at zero temperature are in good agreement with those obtained with the Fermi Hypernetted Chain variational method by Akmal et al. [2]. Furthermore, masses and radii of neutron stars calculated with this EOS of nucleon matter are consistent with recent observational data. It is worth noting that this EOS of nucleon matter is applicable to realistic numerical simulations of core-collapse supernovae, as confirmed in Ref. [3].

In this study, we extend the above cluster variational method for nucleon matter to calculate the energy of hyperonic nuclear matter composed of nucleons (N), Λ and Σ^- hyperons. Following the study in Ref. [1], we employ the AV18 and UIX potentials as interactions among nucleons. For ΛN and the even-state part of the $\Lambda\Lambda$ interactions, we use central potentials which are constructed by Hiyama et al. so that few-body calculations for single- and double-Λ hypernuclei with those interactions reproduce the experimental data on their energy eigenvalues [4, 5]. On the other hand, there is no experimental data on the odd-state part of the $\Lambda\Lambda$ interaction. Hence, we prepare four different models for the odd-state part of the $\Lambda\Lambda$ interaction to investigate the effects of this odd-state $\Lambda\Lambda$ interaction on the static properties of neutron stars. We also use the simple $\Sigma^- N$ potential, which is determined so that the single particle potential of Σ^- in normal nuclear matter reproduces the empirical value.

Using those baryon interactions, we calculate energies of hyperonic nuclear matter by the cluster variational method. The two-body energy E_2 is expressed as the expectation value of the two-body Hamiltonian calculated with the Jastrow wave function in the two-body cluster approximation. Then, for each odd-state $\Lambda\Lambda$ interaction model, E_2 is minimized with respect to the two-body state-dependent central, tensor, and spin-orbit correlation functions included in the Jastrow wave function with subsidiary constraints. Taking into account the three-nucleon energy E_3 somewhat phenomenologically as in Ref. [1], we then obtain the total energy of hyperonic nuclear matter $E = E_2 + E_3$ for each odd-state $\Lambda\Lambda$ interaction model.

In this presentation, we will report the properties of the obtained EOSs for neutron star matter with Λ and Σ^- hyperons, and discuss the effects of the odd-state part of the $\Lambda\Lambda$ interaction on the structure of neutron stars. Furthermore, we will take into account a three-baryon repulsive force in order to explain the observational data on heavy neutron stars.

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