Variational study of the equation of state for neutron star matter with hyperons†

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The equation of state (EOS) for dense nuclear matter plays a crucial role in the study of neutron star (NS) structure. As there are relatively large uncertainties in hyperon-nucleon (YN) and hyperon-hyperon (YY) interactions, the fraction of hyperons in NS matter is still far from being understood. In particular, recently observed masses of PSRs J1614-2230 ($M = 1.97 \pm 0.04 M_\odot$)1) and J0348+0432 ($M = 2.01 \pm 0.04 M_\odot$)2) impose severe constraints on the EOS of nuclear matter including hyperons. In this report, we investigate how uncertainty in the odd-state part of bare $\Lambda\Lambda$ interactions affects the structure of NSs by using EOSs constructed with the cluster variational method for hyperonic nuclear matter containing Λ and Σ^- hyperons.

Following the cluster variational method for pure nucleon matter3), we use the Hamiltonian composed of bare baryon interactions. For the nucleon sector, the Argonne v18 two-nucleon potential and the Urbana IX three-nucleon potential are adopted. For the hyperon sector, central two-body potentials are employed as the ΛN, $\Sigma^- N$, and $\Lambda\Lambda$ interactions4,5), which are constructed to reproduce the experimental data of hypernuclei. Here, it is noted that there are no experimental data on double-Λ hypernuclei to determine the odd-state part of the $\Lambda\Lambda$ interaction. Therefore, we prepare four different odd-state $\Lambda\Lambda$ interactions (Type 1–4), whose parameters are chosen so that the odd-state $\Lambda\Lambda$ interaction becomes monotonically more repulsive from Type 1 to Type 4. Using these baryon interactions, we calculate the energies of hyperonic nuclear matter for each odd-state $\Lambda\Lambda$ interaction model and apply the obtained EOSs to calculations of the NS structure.

The numerical results are shown in Table 1. It is seen that the onset density of Λ in NS matter is insensitive to the odd-state $\Lambda\Lambda$ interaction, whereas that of Σ^- decreases as the odd-state $\Lambda\Lambda$ interaction becomes more repulsive. Furthermore, the obtained maximum mass of NSs increases with the repulsion of the odd-state $\Lambda\Lambda$ interaction, but it is still smaller than the recently observed masses of heavy NSs1,2).

Table 1. Onset densities of Λ and Σ^- hyperons and maximum masses of NSs for four different odd-state $\Lambda\Lambda$ interactions. The values of the onset densities are given in fm^{-3} and the maximum masses are in $M_\odot$.

$\Lambda\Lambda$ interaction	Type 1	Type 2	Type 3	Type 4
Λ onset density	0.42	0.42	0.42	0.42
Σ^- onset density	0.76	0.72	0.70	0.68
Maximum mass	1.48	1.53	1.57	1.62

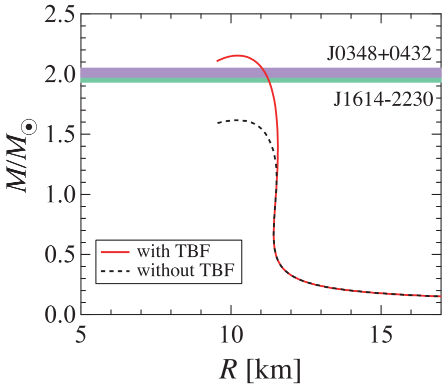

Fig. 1. Mass-radius relations of NSs obtained from EOSs based on the most repulsive odd-state $\Lambda\Lambda$ interaction (Type 4) with and without a phenomenological three-baryon force (TBF). The horizontal bands show the masses of PSRs J1614-22301) and J 0348+04322).

Therefore, we finally consider a phenomenological three-baryon force (TBF) for YNN, YYN, and YYY systems6) in order to explain the masses of heavy NSs. Figure 1 shows the mass-radius relations of NSs obtained from the EOS with the most repulsive odd-state $\Lambda\Lambda$ interaction (Type 4) including the hyperon TBF. Also shown is the result without the hyperon TBF. The maximum mass with the TBF becomes larger than that without the TBF due to the strong repulsion among three baryons. In Fig. 1, the horizontal green and purple bands show the masses of PSRs J1614-22301) and J0348+04322), respectively. It is found that the obtained result with TBF is consistent with these observations. The influence of the TBF on the NS structure is discussed in more detail in Ref.7).

References

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