Effects of Fock term, tensor coupling and baryon structure variation on a neutron star [1]

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Introduction

Recently, the precise observation finds the pulsar with the mass of $1.97 \pm 0.04 M_\odot$ [2]. It is, however, difficult to explain the observed mass by the equation of state (EOS) calculated in relativistic Hartree (H) approximation, because the inclusion of hyperons (Y) makes the EOS soft and thus reduces the maximum mass of a neutron star. Thus, it seems very urgent to consider how this discrepancy can be reconciled. It may be necessary to first study the effects of the Fock term, the tensor couplings of vector mesons and the baryon structure change in matter, and see how those effects contribute to the EOS or the maximum mass of a neutron star.

Quark-Meson Coupling (QMC) Model

We study the properties of nuclear and neutron matter within relativistic Hartree-Fock (HF) approximation, where the pion exchange and the tensor couplings of vector mesons to baryons (B) are included in the Fock term.

- Lagrangian density for dense matter in QMC model

$$\mathcal{L} = \mathcal{L}_B + \mathcal{L}_\ell + \mathcal{L}_M + \mathcal{L}_{int},$$

$$\mathcal{L}_{int} = \sum_B \bar{\psi}_B \left[g_{\sigma B}(\sigma)\sigma - g_{\omega B}\gamma_\mu \omega^\mu + \frac{f_{\omega B}}{2\mathcal{M}} \sigma_{\mu\nu}\partial^\nu \omega^\mu - g_{\rho B}\gamma_\mu \vec{\rho}^\mu \cdot \vec{I}_B + \frac{f_{\rho B}}{2\mathcal{M}} \sigma_{\mu\nu}\partial^\nu \vec{\rho}^\mu \cdot \vec{I}_B - \frac{f_{\pi B}}{m_\pi}\gamma_5\gamma_\mu \partial^\mu \vec{\pi} \cdot \vec{I}_B \right] \psi_B$$

- Using QMC and chiral QMC (CQMC)† model, we consider the variation of the quark substructure of baryon in matter.

$$g_{\sigma B}(\sigma) = g_{\sigma B} b_B \left[1 - \frac{a_B}{2}(g_{\sigma N}\sigma) \right], \quad a_B, b_B\text{: parameter}$$

If we set $a_B = 0$ and $b_B = 1$, $g_{\sigma B}(\sigma)$ is identical to the σ-B coupling constant in Quantum Hadrodynamics (QHD).

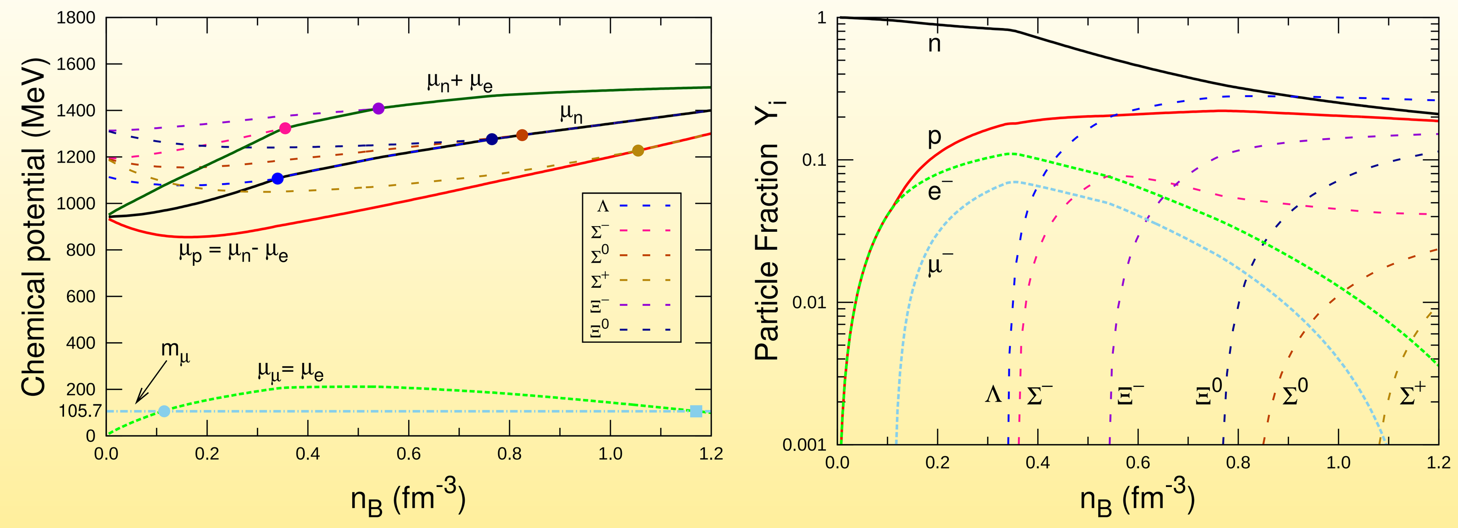
† CQMC model is recently extended to include the quark-quark hyperfine interaction due to the gluon and pion exchanges based on chiral symmetry.

∗ Determination of coupling constants $g_{\sigma N}$ and $g_{\omega N}$: to fit the saturation condition (H and HF), meson-Y: quark model (H), Nijmegen extended-soft-core (ESC) model [3] (HF).

Results and Discussions

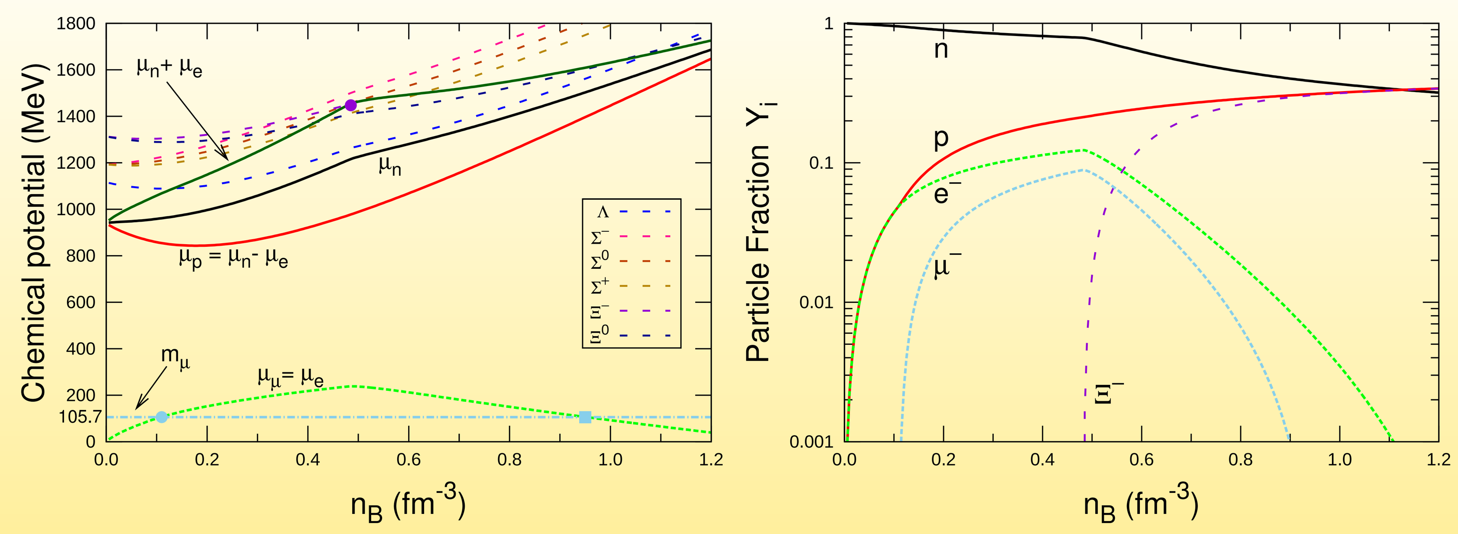
In a neutron star, the charge neutrality and the β equilibrium under weak processes are realized. Under these conditions, we calculate the EOS for neutron matter and solve the Tolman-Oppenheimer-Volkoff (TOV) equation.

- Hartree (H) calculation in QMC model



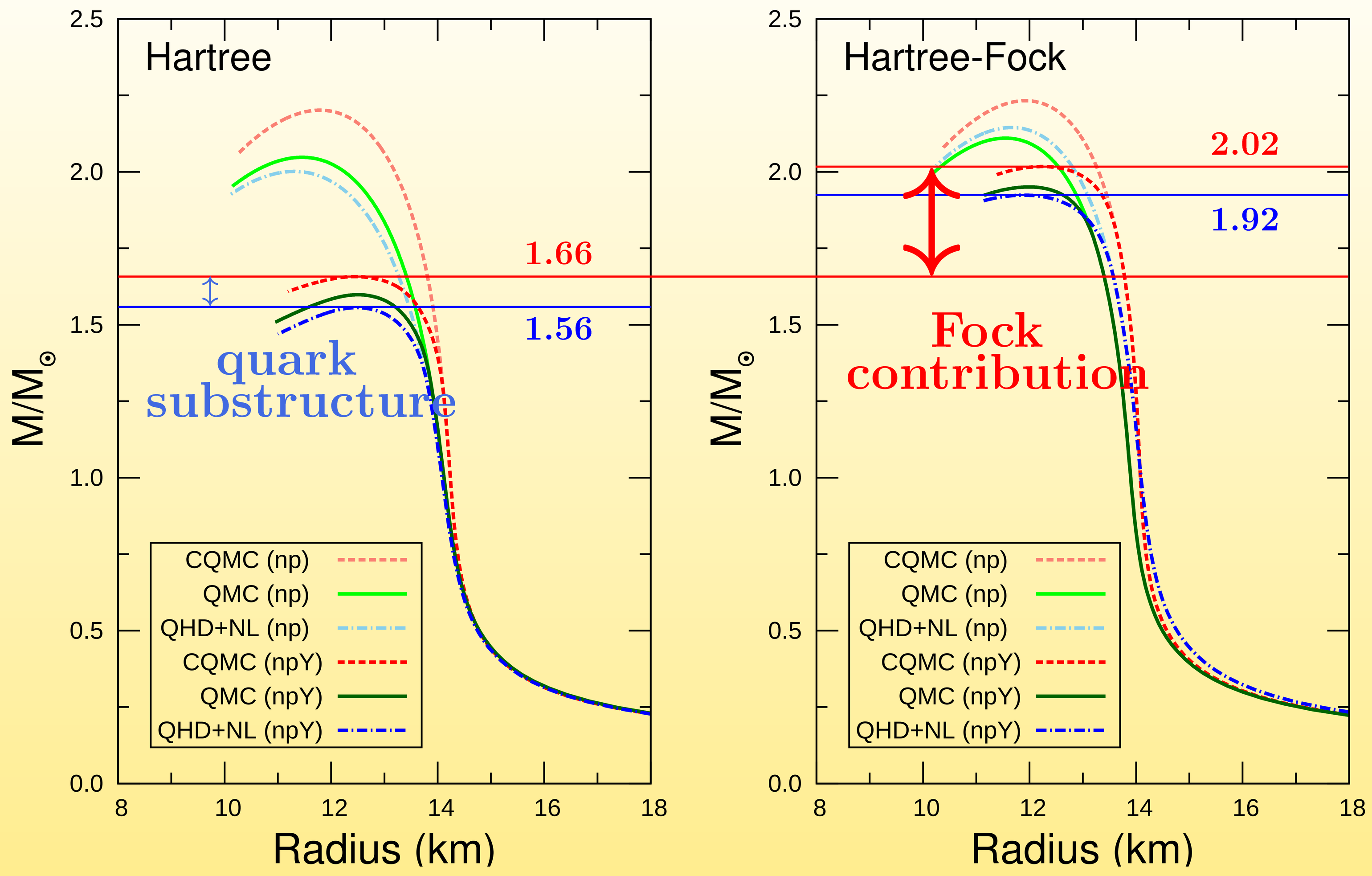
All hyperons are populated ⇒ soft EOS

- Hartree-Fock (HF) calculation in QMC model



Only the Ξ^- appears ⇒ stiff EOS

- Neutron-star mass as a function of the radius



Summary and Future Works

- The present calculation can produce the maximum neutron-star mass of $\sim 2.0 M_\odot$, which is consistent with the recently observed mass, $1.97 \pm 0.04 M_\odot$ [2].
- The Fock contribution is very important and, particularly, the inclusion of tensor coupling is necessary to obtain such large mass.
- The in-medium variation of baryon structure also makes the EOS hard and thus it enhances the mass of a neutron star.

∗ The degrees of freedom of Δ isobar.

∗ The form factor, the π, K-meson exchange and the baryon mixing in the Fock diagram.

∗ The possibility of meson condensates and/or quark matter.

References

[1] T. Miyatsu, T. Katayama, K. Saito, Phys. Lett. B 709 (2012) 242.
[2] P. Demorest, T. Pennucci, S. Ransom, M. Roberts and J. Hessels, Nature 467 (2010) 1081.
[3] T. A. Rijken, M. M. Nagels and Y. Yamamoto, Prog. Theor. Phys. Suppl. 185 (2010) 14.