Effects of Meson Mass Reduction on the Properties of Neutron Star Matter

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We investigate the effects of meson-mass reduction on the properties of the neutron star matter. We adopt the Brown-Rho scaling law to take into account density dependence of meson masses in the quantum hadrodynamics, quark-meson coupling and modified quark-meson coupling models. It is found that the equation of state becomes stiff when the mass of meson is reduced in dense medium. We discuss its implication on the properties of the neutron star.

Several theoretical studies based on different approaches predicted the mass of hadrons in medium. Indeed, recent experimental results from CERES/NA45 and KEK-PS E325 suggested possible reduction of $\rho$ and $\omega$ meson masses in medium. In view of these previous theoretical and experimental studies, inclusion of the effects of the hadron mass reduction in dense nuclear matter is an interesting subject.

There are several models for describing nuclear matter, some of which include quantum hadrodynamics (QHD), quark-meson coupling (QMC) and modified quark-meson coupling (MQMC) models. In these models, coupling constants and some other parameters are adjusted to reproduce the binding energy (= 16.0 MeV) at the saturation density ($\rho_0 = 0.17 \text{ fm}^{-3}$). As a means of incorporating the hadron mass change in medium, we may employ the scaling law advocated by Brown and Rho (BR)

$$\frac{m^*_\sigma}{m_\sigma} = \frac{m^*_\omega}{m_\omega} = \frac{m^*_\rho}{m_\rho} = \left(1 + y \frac{\rho}{\rho_0}\right)^{-1}.$$  

In the present work we use different models for nuclear matter and study the effects of BR scaling on the equation of state (EOS) and particle fraction of the neutron star matter. The models we use and test against each other include QHD, QMC, MQMC, QHD with BR scaling (QHD-BR), QMC with BR scaling (QMC-BR) and MQMC with BR scaling (MQMC-BR).

Neutron star matter is characterized by the charge neutrality ($\rho_p = \rho_e + \rho_\mu$) and $\beta$-equilibrium ($\mu_n = \mu_p + \mu_e + \mu_\mu$) where $\mu_i$ is the chemical potential of the particle $i$ ($i = n, p, e, \mu$). These two relations determine the number of neutrons, protons, electrons and muons. \(^1\)

\(^1\)The number of muons are determined from the chemical equilibration condition with electrons, $\mu_e = \mu_\mu$. 

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Figure 1 shows the energy density and the pressure with respect to the matter density. The energy densities obtained by including the BR scaling increase faster than those without including the effects of meson mass reduction. A similar behavior is observed in the pressure. Fast increase of energy density and pressure leads to stiff EOS. Stiff EOS of BR-scaled models is due to a large repulsive contribution generated by the $\omega$-exchanges in the intermediate and high densities.

Matter composition is presented in Fig. 2. Matter composition profiles for QHD, QMC and MQMC without including BR scaling show similar behaviors. But when BR scaling is incorporated, the fraction of the proton is significantly enhanced. The enhancement of proton fraction originates from the relatively small effective mass of the nucleon in the BR-scaled model.

Maximum mass of the neutron star is sensitive to the EOS. The maximum mass of the neutron star in the QHD is $\sim 1.98 M_\odot$ \cite{10}. As the EOS gets stiffer, the maximum mass of the neutron star becomes larger. Thus, we may expect QHD-BR to give us a larger maximum mass. Similarly, QMC-BR and MQMC-BR may yield a larger neutron star mass than QMC and MQMC, respectively. However, more quantitative calculations require complete inclusion of the components of the baryon octet. When heavy baryons are taken into account, fast-growing chemical potential of the neutron will allow early onset of hyperon fractions, which will make the EOS very soft. Therefore the reduction of meson masses will result in very soft EOS which will, in turn, lower the maximum mass of the neutron star substantially.

Also, a large proton fraction at relatively low densities may allow the direct URCA process ($n \rightarrow p + e^- + \bar{\nu}_e$) to occur at low densities. Direct URCA process is known as the fastest cooling mechanism in the thermal evolution of the neutron star. In addition, existence of hyperons at low densities would cause similar fast cooling mechanism to occur efficiently at low densities.
In summary, we have investigated the effects of the meson-mass reduction on the properties of the neutron star matter. We have used the BR-scaling law as a way of incorporating the mass reduction. We find that the mass reduction makes the EOS stiff and causes the proton fraction to build up quickly at low densities, which can lead to substantially different properties and evolution of the neutron star.

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