PROCEEDINGS OF SCIENCE

Cold dense quark matter and interior structure of hybrid neutron stars

H. Chen* **and J.-B. Wei**
School of Mathematics and Physics, China University of Geosciences (Wuhan), China
E-mail: huanchen@cug.edu.cn,517391121@qq.com

M. Baldo, G. F. Burgio and H.-J Schulze
Sezione di Catania, INFN, Italy
E-mail:
baldo@ct.infn.it,fiorella.burgio@ct.infn.it,schulze@ct.infn.it

We investigate a Dyson-Schwinger quark model with Ball-Chiu construction for quark gluon vertex and compare with our previous results with rainbow approximation. Combining with the hadronic equation of state obtained with Brueckner-Hartree-Fock (BHF) many-body approach, we calculate the equation of state in neutron stars with the hadron-quark phase transition and the interior structure of hybrid neutron stars. We find hybrid neutron stars with two-solar-mass and that the difference due to different quark-gluon vertex models can be compensated by adjusting parameters in the gluon propagator model.

9th International Workshop on Critical Point and Onset of Deconfinement - CPOD2014,
17-21 November 2014
ZiF (Center of Interdisciplinary Research), University of Bielefeld, Germany

*Speaker.

PoS(CPOD2014)062

1. Introduction

The possible appearance of quark matter (QM) in the interior of massive neutron stars (NS) is one of the main issues in the physics of these compact objects. The value of the maximum mass of a NS is probably one of the physical quantities that are most sensitive to the EOS of QM. Unfortunately, the QM EOS is poorly known at zero temperature and at the high baryonic density appropriate for NS. One has, therefore, to rely on models of QM, which are usually too far from real QCD. Thus, we try to develop quark models in the framework of the Dyson-Schwinger equations(DSE)[1, 2, 3], which is well based on QCD. In the present work, we study the DSE wtih the Ball-Chiu (BC) vertex[4] to improve our previous quark model with Rainbow approximation[5]. To describe the hadronic phase in compact stars, we combine a definite baryonic EOS, developed within the Brueckner-Hartree-Fock (BHF) many-body approach of nuclear matter,

2. Equation of State of Dense Matter

2.1 EOS of hadronic matter within Brueckner theory

The Brueckner-Bethe-Goldstone theory is based on a linked cluster expansion of the energy per nucleon of nuclear matter (see Ref. [6], chapter 1 and references therein). The basic input quantities in the Bethe-Goldstone equation are the nucleon-nucleon (NN) two-body potentials V. In this work, we chose the EoS with the Bonn B potential, supplemented by a compatible microscopic three body forces [7]. Within the Brueckner theory, the EOS with presence of hyperons is very soft, reducing the maximal mass of neutron stars to be less than 1.4 solar mass[7]. Besides, with our Dyson-Schwinger quark model, the hadron-quark phase transition takes place only when hyperons are excluded [5]. Therefore, we neglect hyperons in this work.

2.2 Quark Matter

We work in the formalism of DSE in Euclidean space. The DSE of the quark propagator reads

$$\begin{aligned} S(p;\mu)^{-1} = \; & Z_2\,[i\vec{\gamma}\cdot\vec{p}+i\gamma_4(p_4+i\mu)+m_q] \\ & +Z_1\int^{\Lambda}\frac{d^4q}{(2\pi)^4}\,g^2(\mu)D_{\rho\sigma}(p-q;\mu)\frac{\lambda^a}{2}\gamma_\rho S(q;\mu)\Gamma^a_\sigma(q,p;\mu) \end{aligned} \tag{2.1}$$

In our previous work, we worked with 'Rainbow approximation', i.e. $\Gamma_\nu(q,k)=\gamma_\nu$. Now we employ the BC vertex, which satisfies the Ward Identity of QED. The form of BC at finite chemical potential is developed in [4],

$$\begin{aligned} i\Gamma_\sigma(k,\ell;\mu) &= i\Sigma_A(k,\ell;\mu)\gamma_\sigma^\perp+i\Sigma_C(k,\ell;\mu)\gamma_\sigma^\parallel+(\tilde{k}+\tilde{\ell})_\sigma \\ & \quad \left[\frac{i}{2}\gamma^\perp\cdot(\tilde{k}+\tilde{\ell})\Delta_A(\tilde{k},\tilde{\ell};\mu)+\frac{i}{2}\gamma^\parallel\cdot(\tilde{k}+\tilde{\ell})\Delta_C(\tilde{k},\tilde{\ell};\mu)+\Delta_B(\tilde{k},\tilde{\ell};\mu)\right] \\ \Sigma_F(k,\ell;\mu) &= \frac{1}{2}\left[F(\vec{k}^2,k_4;\mu)+F(\vec{\ell}^2,\ell_4;\mu)\right] \\ \Delta_F(\tilde{k},\tilde{\ell};\mu) &= \frac{F(\vec{k}^2,k_4;\mu)-F(\vec{\ell}^2,\ell_4;\mu)}{\tilde{k}^2-\tilde{\ell}^2} \end{aligned}$$

where$u = (\vec{0}, \mu)$, $\tilde{k} = k + u$, $\gamma^{\perp} = \gamma - \hat{u}\gamma \cdot \hat{u}$, $\gamma^{\parallel} = \hat{u}\gamma \cdot \hat{u}$, with $\hat{u}^2 = 1$. As to the gluon propagator, we employ the Landau gauge form with an infrared dominant interaction modified by the chemical potential

$$Z_1 g^2 D_{\rho\sigma}(k) = \frac{\mathscr{G}(k^2)}{k^2}\,(\delta_{\rho\sigma} - \frac{k_\rho k_\sigma}{k^2})\,, \tag{2.2}$$

$$4\pi\frac{\mathscr{G}(k^2)}{k^2} = 4\pi^2 d\,\mathrm{e}^{-\alpha\mu_q^2/\omega^2}\,\frac{k^2}{\omega^6} exp(-\frac{k^2}{\omega^2}) \tag{2.3}$$

with $\omega = 0.5GeV$, $d = 1GeV^2$(with Rainbow approximation), $d = 0.5GeV^2$(with BC vertex), $m_{u,d} = 0$, $m_s = 0.115GeV$ and α as a phenomenological parameter. The EOS of cold QM is given following Refs. [4, 8]. We express the quark number density and other thermodynamical quantities as

$$n_q(\mu) \;=\; 6\int \frac{d^3p}{(2\pi)^3}\, f_q(|\vec{p}|;\mu)\,, \tag{2.4}$$

$$f_q(|\vec{p}|;\mu) \;=\; \frac{1}{4\pi}\int_{-\infty}^{\infty} dp_4\, \mathrm{tr}_{\mathrm{D}}\left[-\gamma_4 S_q(p;\mu)\right]\,, \tag{2.5}$$

$$P_q(\mu_q) \;=\; P_q(\mu_{q,0}) + \int_{\mu_{q,0}}^{\mu_q} \mathrm{d}\mu\, n_q(\mu)\,. \tag{2.6}$$

$$P_Q(\mu_u,\mu_d,\mu_s) \;=\; \sum_{q=u,d,s} \tilde{P}_q(\mu_q) - B_{DS} \tag{2.7}$$

$$\tilde{P}_q(\mu_q) \;\equiv\; \int_{\mu_{q,0}}^{\mu_q} \mathrm{d}\mu\, n_q(\mu)\,, \tag{2.8}$$

$$B_{DS} \;\equiv\; -\sum_{q=u,d,s} P_q(\mu_{q,0})\,. \tag{2.9}$$

3. Numerical Results

3.1 single flavor quarks

Based on our quark models, we obtain the density $n_q(\mu_q)$ and $\tilde{P}_q(\mu_q)$, which are shown in Fig.1

3.2 Hadron-Quark Phase Transition in beta stable matter

For the Hadron-Quark phase transition in beta stable matter, we employ the Gibbs conditions for chemical and mechanical equilibrium between both phases as well as global charge neutrality under Glendenning construction

$$\chi\rho_c^Q + (1-\chi)\rho_c^H = 0\,. \tag{3.1}$$

with the volume fraction χ occupied by QM in the mixed phase $n_{BM} = \chi n_{BQ} + (1-\chi)n_{BH}$. Our results of EOS and the fraction of every components of the beta stabled dens matter are shown in Fig. 2 and Fig. 3. The fractions in pure phases are defined as $\lambda_i \equiv \frac{n_i}{n_B}$ for all species, while in the mixed phase, the fractions are given as $\lambda_i \equiv \chi\frac{n_i}{n_B}$ for $i = u, d, s$, $\lambda_i \equiv (1-\chi)\frac{n_i}{n_B}$ for $i = n, p$, and $\lambda_i \equiv \frac{n_i}{n_B}$ for $i = e, \mu$.

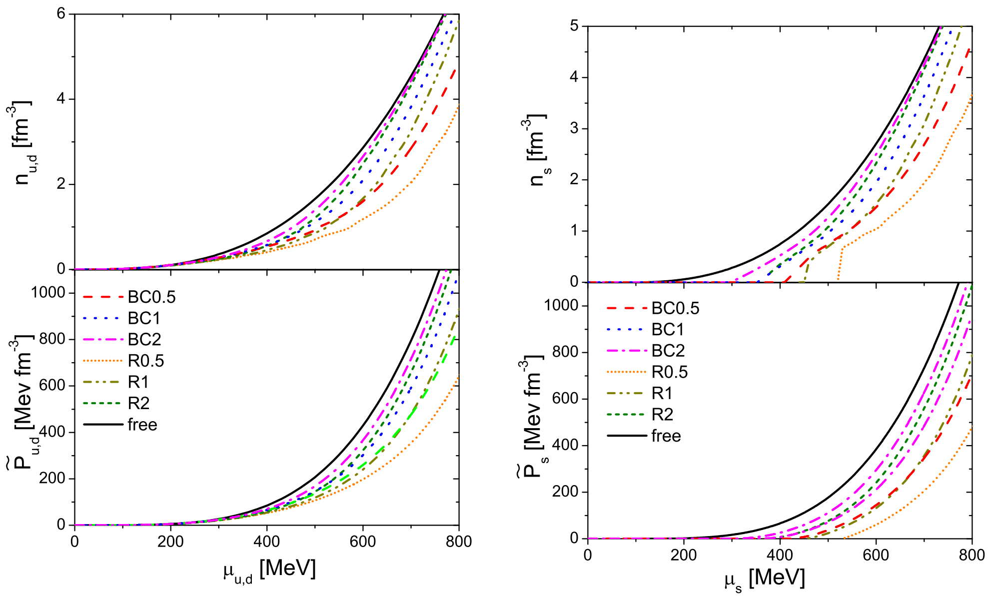

Figure 1: The density $n_q(\mu_q)$(upper) and $\tilde{P}_q(\mu_q)$(lower) of u(d) quark (left) and s quark(right).

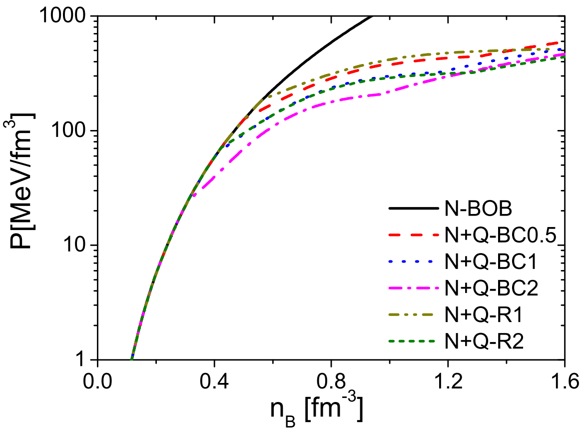

Figure 2: EoS with H-Q phase transition under Glendenning construction.

3.3 Hybrid Stars Structure

We assume that a NS is a spherically symmetric distribution of mass in hydrostatic equilibrium. The equilibrium configurations are obtained by solving the TOV equations. We have used as input the EOS discussed above and shown in Fig. 2. For the description of the NS crust, we have joined the hadronic EOS with the ones by Negele and Vautherin in the medium-density regime, and the ones by Feynman-Metropolis-Teller and Baym-Pethick-Sutherland for the outer crust. Our numerical results are shown in Fig. 4

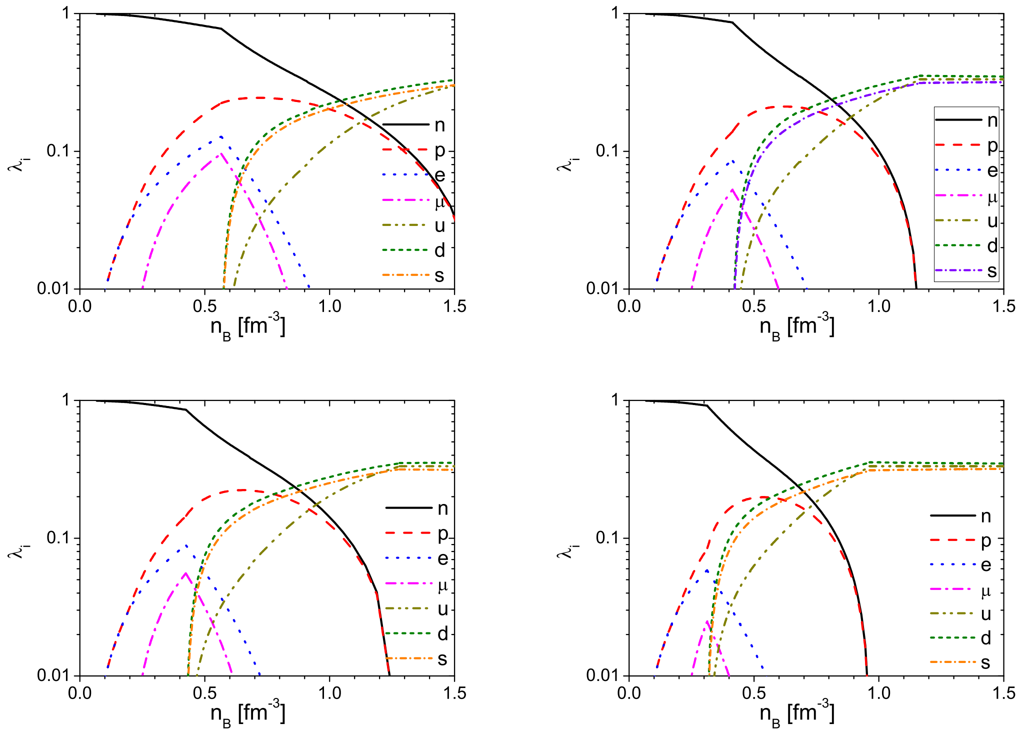

Figure 3: The components of dense matter with H-Q phase transition under Gledenning construction.

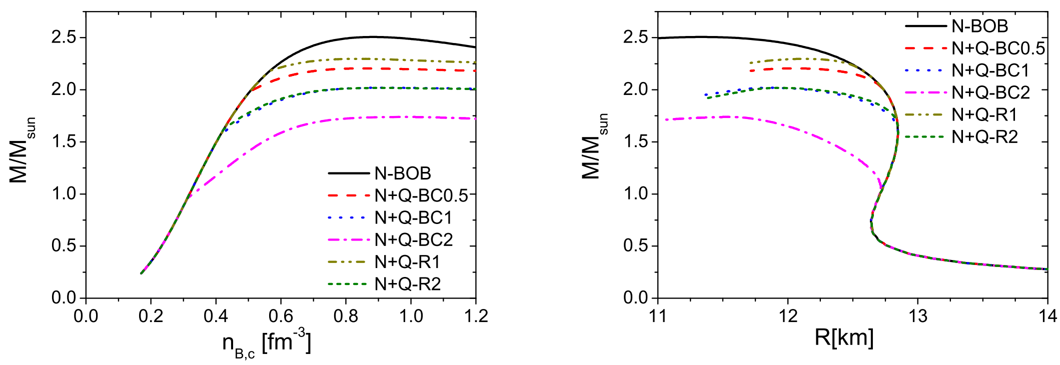

Figure 4: (Color online) Gravitational NS mass vs. the central baryon density (left panel) and the radius (right panel) for different quark EOS combing the BOB hadronic model.

4. Summary and Remarks

We have solved the Dyson-Schwinge equations of quark propagator at finite chemical potentials with Ball-Chiu vertex and a chemical potential dependent effective interaction. Based on the quark propagator, we give the EoS of cold dense quark matter. In combination with a hadronic EOS given by BBG theory with Bonn B NN potential and a compatible microscopic three body forces, we investigate the H-Q phase transition under Glendenning construction. Comparing with results under rainbow approximation with same parameter α, the quark EoS with BC vertex is softer, resulting in smaller phase transition densities and mixed phases regions, as well as smaller maximal mass of hybrid stars. In other words, the quark EOS with BC vertex can be compatible with the present observation of the maximal mass of compact stars, while constraint the parameter α to be smaller values.

References

[1] C. D. Roberts and A. G. Williams, *Prog. Part. Nucl. Phys.* **33**, 477 (1994).

[2] R. Alkofer and L. von Smekal, *Phys. Rep.* **353**, 281 (2001).

[3] C. D. Roberts and S. M. Schmidt, *Prog. Part. Nucl. Phys.* **45**, S1 (2000).

[4] H. Chen, W. Yuan, L. Chang, Y. X. Liu, T. Klähn, and C. D. Roberts, *Phys. Rev.* **D78**, 116015 (2008).

[5] H. Chen, M. Baldo, G. F. Burgio and H.-J. Schulze, *Phys. Rev.* **D84**, 105023 (2011).

[6] M. Baldo, *The many-body theory of the nuclear equation of state, Nuclear Methods and the Nuclear Equation of State, International Review of Nuclear Physics, Vol. 8*, World Scientific, Singapore, 1999.

[7] Z. H. Li and H.-J. Schulze, *Phys. Rev.* **C78**, 028801 (2008).

[8] T. Klähn, C. D. Roberts, L. Chang, H. Chen, and Y. X. Liu, *Phys. Rev.* **C82**, 035801 (2010).