Medium modifications of the nucleon radius and its application on the properties of the slowly rotating neutron star

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Outline

1. Background
   - QHD with Nucleon as point-like particle
   - Nucleon radius impact on equation of state (EOS) and properties of neutron star
2. QHD and QMC with excluded volume
   - EOS with excluded volume
3. Medium modifications of the nucleon radius
4. QHD with medium modifications of the nucleon radius
   - Its implication on EOS and properties of the slowly rotating NS
5. Conclusion and Outlook

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BACKGROUND

- Lagrangian density of QHD[1]:

$$\mathcal{L} = \bar{\psi}[\gamma_\mu(i\partial^\mu - g_\omega\omega^\mu) - (M - g_s\phi)]\psi + \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_s^2\phi^2) - \frac{1}{3!}\kappa\phi^3 - \frac{1}{4}\lambda\phi^4 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \delta\mathcal{L} \quad (1)$$

where $F^{\mu\nu} \equiv \partial^\mu\omega^\nu - \partial^\nu\omega^\mu$.

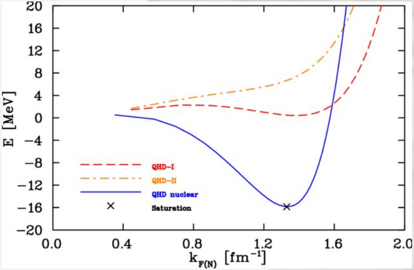
- QHD-I contains scalar(σ), vector-isoscalar (ω)[2]
- QHD-II (QHD-I plus isovector-vector (ρ))
- QHD models based on baryon and meson degree of freedom
- S:In this QHD (Walecka) model, nucleons are assumed as point-particle (no structure)

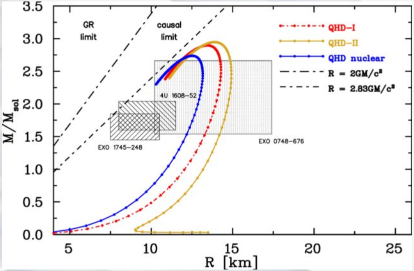
[1] J. D. Carroll, Arxiv:1001.4318

[2] B. Serot and J.D. Walecka, IJMP E6 (1997)

EOS of various QHD type models[3]

- Energy binding as a function Fermi momentum (k_F) of various QHD model
- Prediction of these various of QHD model on properties of static neutron star (Mass-radius relation)

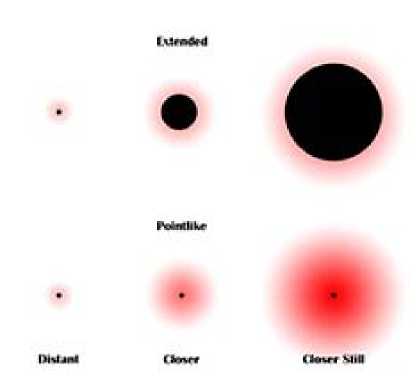




[3] J. D. Carroll, Arxiv:1001.4318

Nucleon as point-like particle[4]

- A point-like particle do not change in size
- The field surrounding it becomes stronger when you look closely

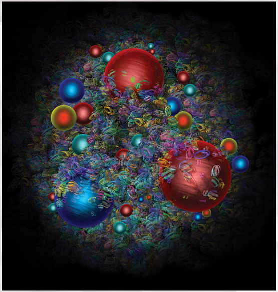


- Q: Is it really true that nucleon is point-like particle??

4 https://www.fnal.gov/pub/today/archive/archive-2013/today13-02-15-NutshellReadMore.html

Nucleon as composite particle[5]

- Nucleon has a size (structure)–Proton radius puzzle (18 years)–> the MUSE experiment
- Structure of nucleon is more complex (valence quarks + sea quarks + gluons)



- Q: What is the impact of the nucleon size in nucleon/nuclear matter models??

[5] https://cerncourier.com/a/the-proton-laid-bare/

QMC model–extended of QHD model

- QMC model is a model which can describe the different phases of hadronic matter in terms of explicit quark-gluon degrees of freedom, proposed by Guichon[6] and extensively investigated by Saito[7]
- The effective mesons couple directly to the quarks in the interior of the nucleons –> effective baryon-meson coupling constant become density dependent
- In the QMC model, nucleon has structure (quark confined in the MIT bag model)
- However the radius of the bag model is not observable and it is different with the nucleon radius
- In medium, the bag radius decreases with increasing the density

[6] P. A. M. Guichon, PLB **200** (1988)

[7] K. Saito and A. W. Thomas, PLB**327** (1994)

LAGRANGIAN QMC MODEL

The effective Lagrangian for a symmetric nuclear matter in the QMC model:

$$\mathscr{L}_{\rm QMC} = \bar{\psi}\left[i\gamma_\mu\partial^\mu - M_N^*(\sigma) - g_\omega\gamma_\mu\omega^\mu\right]\psi + \mathscr{L}_m, \quad (2)$$

The free meson Lagrangian density:

$$\mathscr{L}_m = \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{2}\partial_\mu\omega_\nu\left(\partial^\mu\omega^\nu - \partial^\nu\omega^\mu\right) + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu$$

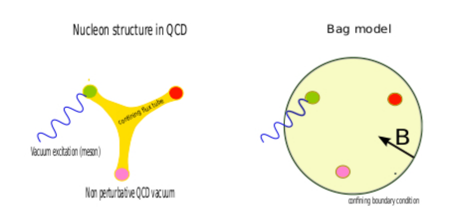


FIGURE: The QCD picture of the nucleon and the bag model [8]

[8] J.Stone *et al.*, Prog.Part.Nucl.Phys. **100** (2018)

Lagrangian QMC model

- In the QMC model, the nuclear matter is treated as a collection of the nucleons that are assumed to be non-overlapping MIT bags
- The Dirac equation for the light quarks inside the bags are given by

$$\left[i\gamma\cdot\partial_x - (m_q - V_\sigma^q) \mp \gamma^0\left(V_\omega^q + \frac{1}{2}V_\rho^q\right)\right]\begin{pmatrix}\psi_u(x)\\ \psi_{\bar{u}}(x)\end{pmatrix} = 0$$

$$\left[i\gamma\cdot\partial_x - (m_q - V_\sigma^q) \mp \gamma^0\left(V_\omega^q - \frac{1}{2}V_\rho^q\right)\right]\begin{pmatrix}\psi_d(x)\\ \psi_{\bar{d}}(x)\end{pmatrix} = 0$$

$$[i\gamma\cdot\partial_x - m_s]\begin{pmatrix}\psi_s(x)\\ \psi_{\bar{s}}(x)\end{pmatrix} = 0, \quad (3)$$

where the effective current quark mass m_q^* is defined as

$$m_q^* \equiv m_q - V_\sigma^q, \quad (4)$$

where m_q is the current quark mass, where $q = (u, d, s)$ and V_σ^q is the scalar potential.

Lagrangian QMC model

The effective nucleon mass:

$$M_N^*(\sigma) \equiv M_N - g_\sigma(\sigma)\,\sigma, \quad (5)$$

Total energy per nucleon:

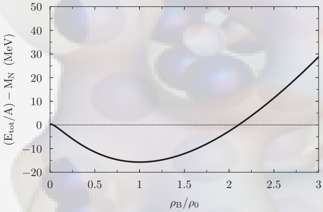
$$E^{\rm tot}/A = \frac{4}{(2\pi)^3\rho_B}\int d\mathbf{k}\,\theta(k_F-|\mathbf{k}|)\sqrt{M_N^{*2}(\sigma)+\mathbf{k}^2} + \frac{m_\sigma^2\sigma^2}{2\rho_B} + \frac{g_\omega^2\rho_B}{2m_\omega^2}. \quad (6)$$

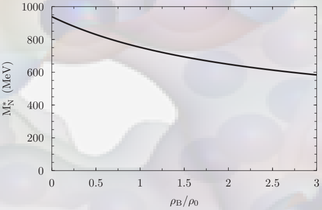
Table: Parameters of the QMC model and the obtained nucleon properties at saturation density $\rho_0 = 0.15$ fm^{-3} for two quark mass values in free space, $m_q = 5.0$. The m_q, M_N^*, and K are given in units of MeV. The parameters are fitted to the free space nucleon mass $M_N = 939$ MeV with $R_N = 0.8$ fm (input), and the nuclear matter saturation properties.

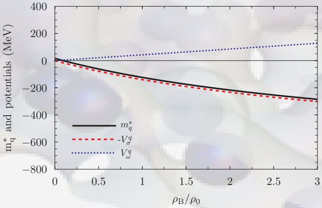
m_q	$g_\sigma^2/4\pi$	$g_\omega^2/4\pi$	$B^{1/4}$	z_N	M_N^*	K
5	5.393	5.304	170.0	3.295	754.6	279.3

Lagrangian QMC model

Energy per nucleon ($E^{tot}/A - M_N$), effective nucleon mass M_N^* and effective quark mass (m_q^*) and the quark potentials (V_σ^q and V_ω^q) for symmetric nuclear matter in the QMC model for the current quark mass $m_q = 16.4$ MeV

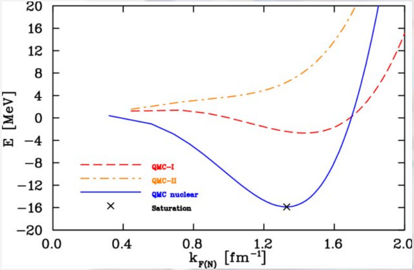


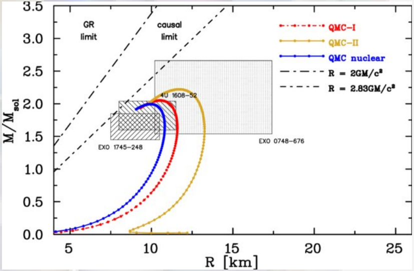




EOS OF VARIOUS QMC MODEL

- Energy binding of the QMC model
- Prediction of the QMC model on properties of neutron star





- Q: The radius of the bag model is not observable and it is different with the nucleon radius. How should we include the size of proton??

This is just beginning

QHD and QMC models with the radius of nucleon

QHD WITH EXCLUDED VOLUME

- Energy density of matter consisting of leptons and composite nucleons with a radius r[9]

$$
\begin{aligned}
\epsilon &= \mathcal{A}[\epsilon_p^k + \epsilon_n^k] + \epsilon_e^k + \epsilon_\mu^k + \epsilon_M(\omega, \sigma, \rho) \\
&+ g_\omega(\rho_p + \rho_n) + \frac{1}{2} g_\rho b_0(\rho_p - \rho_n),
\end{aligned} \tag{7}
$$

where

$$
\begin{aligned}
\epsilon_M &= \epsilon_M^{\text{linear}} + \frac{1}{3} b_2 \sigma^2 + \frac{1}{4} b_3 \sigma^4 - \frac{1}{4} c_3 \omega^4 - \Lambda_\nu g_\rho^2 g_\omega^2 \rho^2 \omega^2, \\
\epsilon_{e,\mu} &= \frac{2}{(2\pi)^3} \int d^2\vec{k} (k^2 + m_{e,\mu}^*)^{1/2} \theta(k - k_F), \\
\epsilon_{p,n} &= \frac{2}{(2\pi)^3} \int d^2\vec{k} (k^2 + m_{p,n}^*)^{1/2} \theta(k - k_F), \\
\mathcal{A} &= \frac{1}{1 + V_p \rho_p' + V_n \rho_n'},
\end{aligned} \tag{8}
$$

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[8] Sulaksono, and Mart, PRC**95** (2017)

QHD WITH EXCLUDED VOLUME

- Proton or neutron and the corresponding scalar densities[10]

$$\rho_{p,n} = \mathcal{A}\rho'_{p,n},$$
$$\rho_{s,i} = \mathcal{A}\rho'_{s,i}, \quad \text{where} \quad i = p, n,$$
$$V_p \sim V_n = V_N \quad \text{where} \quad V_N = \frac{4\pi r_N^3}{3}. \tag{9}$$

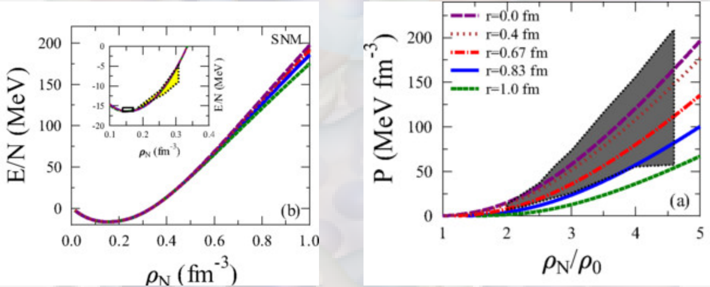
- Pressure of matter can be obtained

$$P = \rho^2 \frac{d(\epsilon/\rho)}{d\rho}. \tag{10}$$

[10] Sulaksono, and Mart, PRC**95** (2017)

QHD WITH EXCLUDED VOLUME

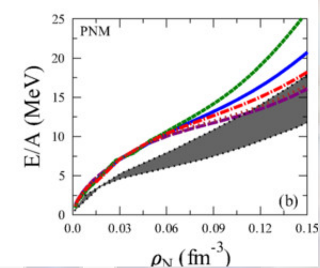
- Energy per nucleon and pressure as a function of ρ_N and ρ_N/ρ_0, respectively, for symmetric nuclear matter (SNM)[11]

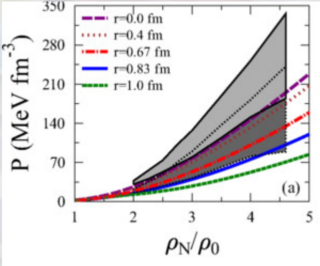


[11] Sulaksono, and Mart, PRC**95** (2017)

QHD WITH EXCLUDED VOLUME

- Energy per nucleon and pressure for pure neutron matter (PNM)[12]

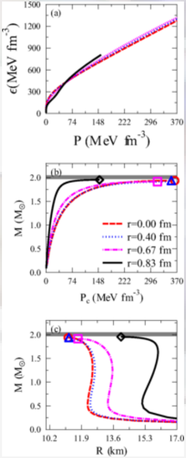


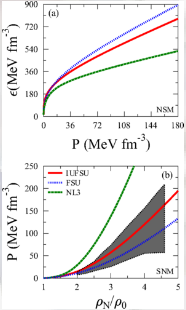


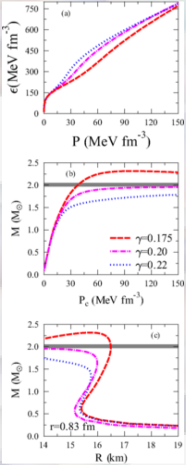
[12] Sulaksono, and Mart, PRC**95** (2017)

QHD WITH EXCLUDED VOLUME

- Impact of the nucleon radius (via excluded volume) on the neutron star properties[13]



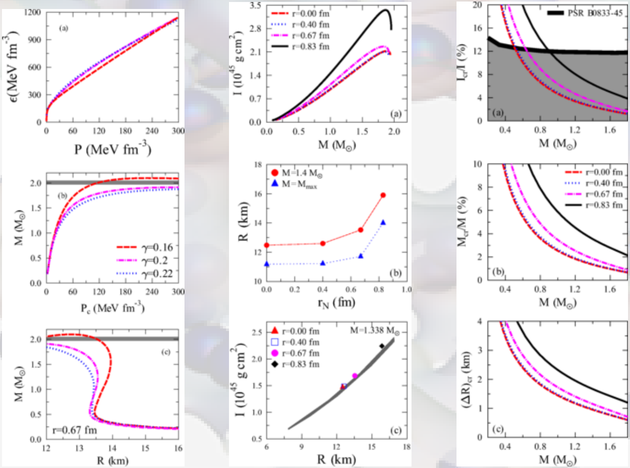




[13] Sulaksono, and Mart, PRC**95** (2017)

QHD WITH EXCLUDED VOLUME

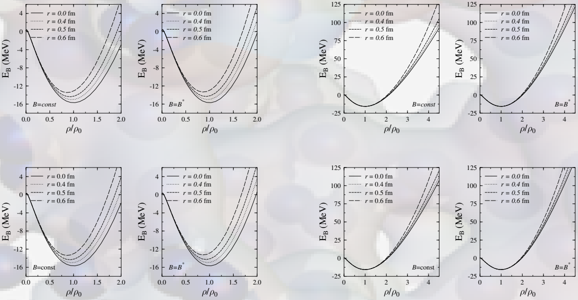
- Impact of the nucleon radius (via excluded volume) on the neutron star properties[14]



[14] Sulaksono, and Mart, PRC95 (2017)

QMC with excluded volume

- Energy per nucleon of nuclear matter as a function ρ_B/ρ_0 for various hard core radii (left panel)
- Energy per nucleon of nuclear matter as a function ρ_B/ρ_0 with refitting coupling constant for various hard core radii (right panel)[15]



- Q: The proton radius used is in the free space. What happen if we consider the medium modification of the nucleon radius??

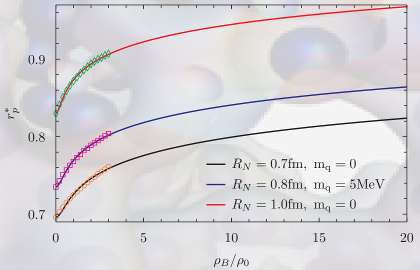
[15] P. K. Panda *et.al*, PRC**65** (2002)

MEDIUM MODIFICATIONS OF THE NUCLEON RADIUS

QHD and QMC models with the medium modifications of the nucleon radius

Medium modifications of nucleon radius[17]

- Nucleon radius in medium for various nucleon bag radius $R_N = (0.7, 0.8, 1.0)$ fm with the current quark mass $m_q = (0, 5)$ MeV.

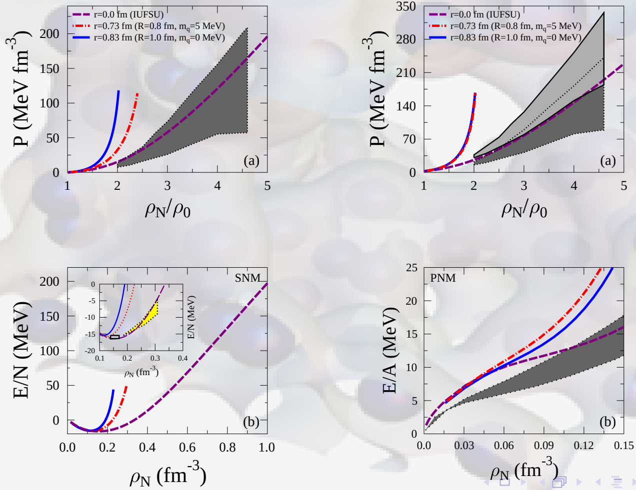


- At saturation density (ρ_0), the nucleon radius increases 25 %
- $\rho_B = 3\ \rho_0$ the nucleon radius increases about 50 % and for higher density the increasing rate of radius is more pronounced, which is consistent with recent paper of Ref[16]

[16] A. G. Miller, ArxiV:1907.00110

[17] D.H.Lu, AW. Thomas, Kazuo Tsushima *et. al*, PLB **417** (1998)

QHD with excluded volume and medium modification of proton radius (PRELIMINARY RESULT)



Summary and Outlook

- We have shown the effect of radius proton in free space as well as in medium and EOS becomes stiff when we consider the in-medium modifications of proton radius
- Medium modifications of radius proton potentially give the high mass Neutron star and smaller the moment of inertia based on the results of EOS obtained
- Next, we will refit the QHD and QMC with various medium modifications of radius proton to produce the correct saturation point and satisfy the experimental constraints, as the results of the QMC with the radius proton in free space
- It is also possible to check the effects of medium modification of the nucleon radius using other models such as the quark mean field model[18]

[18] Zhen-Yu, Ang-Li, PRD**97** (2018) or Zhen-Yu, Ang Li, Jin-Niu Hu, Hong Shen, PRC**99** (2019)

THANK YOU VERY MUCH

FOR YOUR ATTENTION