Neutron stars with crossover to color superconducting quark matter

Elena-Oana Hanu (PhD student)

Supervisors: **Prof. Dr. David Blaschke**
Prof. Dr. Alexandru Jipa

Department of Nuclear Physics
Faculty of Physics
University of Bucharest

June 21, 2022

Overview

1. Introduction
2. Equation of state
3. Results

Introduction

The quest for the structure of the phase diagram of quantum chromodynamics (QCD) in the plane of temperature and baryon density is one of the great challenges in experimental and theoretical particle and nuclear physics

⇒ The structure of the QCD phase diagram is likely to be a crossover all over

⇒ One approach to a unified description of the EoS of hadronic and quark matter phases is based on an interpolation between a hadron resonance gas EoS and a perturbative QCD approach to the QGP using a switching function

⇒ It was followed the idea to fix the switch function in the $T = 0$ limit by a comparison with neutron star phenomenology

Quark matter

It was used the form of EoS for color superconducting quark matter phases that was suggested in Alford *et al.*:

$$P_q = \frac{3}{4\pi^2} a_4 \left(\frac{\mu}{3}\right)^4 + \frac{3}{\pi^2}\Delta^2 \left(\frac{\mu}{3}\right)^2 - B_{eff} \tag{1}$$

It was considerated massless quarks ($m_u = m_d = m_s = 0$) and for the coefficient $a_4 = 1 - 2\alpha_s/\pi$ was used constant values $a_4 = 0.3$ or 0.7. The quantities such as quark number density and energy density were derived from the pressure formula (1)

Quark matter

An interesting quantity is squared speed of sound, which serves as a measure for the stiffness of the EoS:

$$c_s^2(\mu) = \frac{dP_q(\mu)}{d\varepsilon(\mu)} = \frac{n_q(\mu)}{\mu d n_q(\mu)/d\mu} \tag{2}$$

Two limits have to be discussed:

- For normal quark matter when $\Delta = 0$, the $c_s^2 = 1/3$
- Immediatelly after the deconfinement when $\Delta \approx 150$ MeV , the $c_s^2 = 1/2$

For zero temperature quark matter in β equilibrium, the $c_s^2(\varepsilon) = 0.5 \pm 0.1$ (attaining almost constant values) depending on the values of vector meson and diquark coupling

Neutron matter

The hadronic matter phase was modelled using the description of pure neutron matter as given in the **nonlinear Walecka model**. It is an effective field theory that describes the residual strong nuclear force between nucleons, via exchange of sigma and omega mesons.

$$P_h(n) = P_{FG} + \frac{1}{2}\left[\left(\frac{g_\omega^2}{m_\omega^2}\right) + \frac{1}{4}\left(\frac{g_\rho^2}{m_\rho^2}\right)\right] n^2 - \frac{1}{2}\left(\frac{m_\sigma^2}{g_\sigma^2}\right)(g_\sigma \sigma)^2 - \frac{1}{3} bm (g_\sigma \sigma)^3 - \frac{1}{4} c (g_\sigma \sigma)^4 \tag{3}$$

$$\varepsilon_h(n) = \varepsilon_{FG} + \frac{1}{2}\left[\left(\frac{g_\omega^2}{m_\omega^2}\right) + \frac{1}{4}\left(\frac{g_\rho^2}{m_\rho^2}\right)\right] n^2 + \frac{1}{2}\left(\frac{m_\sigma^2}{g_\sigma^2}\right)(g_\sigma \sigma)^2 + \frac{1}{3} bm (g_\sigma \sigma)^3 + \frac{1}{4} c (g_\sigma \sigma)^4 \tag{4}$$

Crossover EoS

In order to construct the crossover transition from neutron matter to color superconducting quark matter, we apply the interpolation method based on a **switching function** for describing this crossover in neutron stars:

$$P(\mu) = S(\mu)P_q(\mu) + [1 - S(\mu)]P_h(\mu) \tag{5}$$

where for the switching function it was adopted the generalized form:

$$S(\mu) = exp[-(\mu_0/\mu)^r] \tag{6}$$

where r=4, 5, 6 and μ_0 was varied from 1200 to 2600 MeV.

The other thermodynamic quantities were derives from the pressure $P(\mu)$.

Calculation of astrophysical observables

From the EoS, possible neutron star radii and masses were derived. To evaluate the neutron star properties one has to solve the **Tolman-Oppenheimer-Volkoff (TOV) equations** for a nonrotating, spherical-symmetric star:

$$\frac{dP(r)}{dr} = \frac{G(\varepsilon(r) + P(r))(M(r) + 4\pi r^3 P(r))}{r(r - 2GM(r))} \tag{7}$$

$$\frac{dM(r)}{dr} = 4\pi r^2 \varepsilon(r) \tag{8}$$

These can directly be compared to observations from the combined observations by NICER and XMM Newton. Additionally, the tidal deformability can be calculated and be compared to the constraint obtained from the gravitational wave signal that was observed for the binary neutron star merger GW170818.

Results

For the parametrization of the NLW model, the values given in the textbook by Glendenning were used.

It was distinguished **two classes of parametrizations**:

- The first class has an $O(\alpha_s)$ correction to the quark matter EoS that results in a moderate stiffening of the equation of state with a typical value of a_4=0.7.
- The second class uses much lower values for the a_4 parameter (0.3 or lower)

For characterizing the models it was used a shorthand notation with three parameters in round brackets: $(a_4, \Delta[MeV], B_{eff}^{1/4}[MeV])$

Results

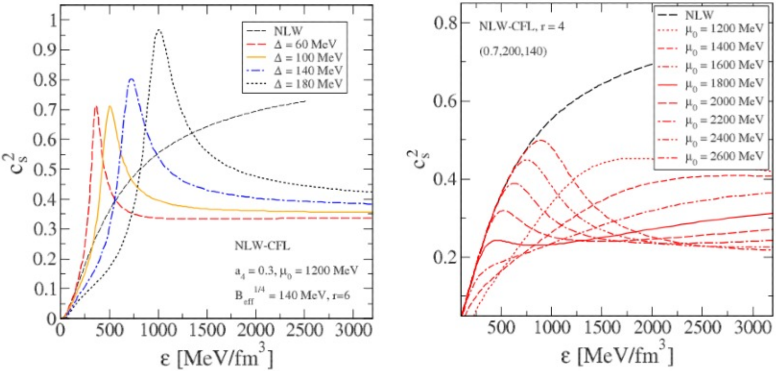

Figure 1: Speed of sound squared as a function of energy density for the two classes of parametrization

Results

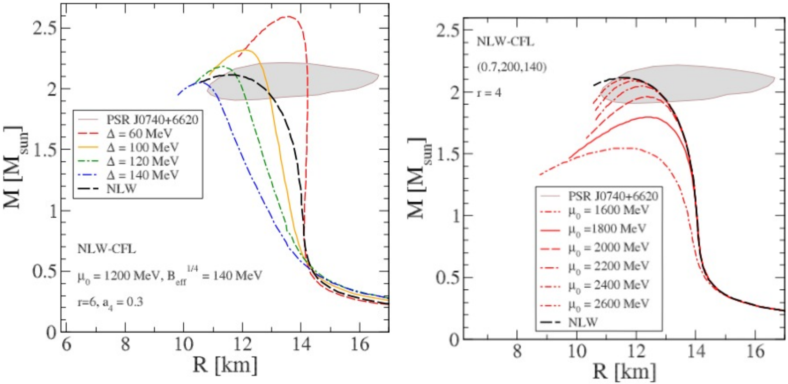

Figure 2: Mass vs. radius for the considered neutron stars of the two classes of parametrization

Results

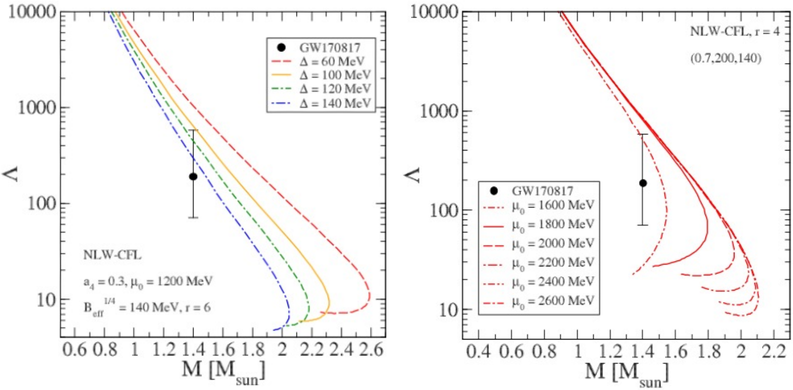

Figure 3: Tidal deformability vs. mass for the considered neutron stars of the two classes of parametrization

Conclusions - First parametrization

From the comparison with the recent mass-radius data of the massive pulsar PSR J0740+6620 that were obtained by the Maryland-Illinois team of the NICER collaboration, **for the first class of models**:

- A too small value for the switch function parameter $\mu_0 < 1400$ MeV could be excluded, because it would lead to a too low maximum mass of pulsars (excluded by observation)
- When considering the tidal deformability constraint, it was found no parametrization of the quark matter model and the switching function that would simultaneously fulfill both constraints from neutron star phenomenology.

Conclusions - Second parametrization

For the second class of models:

- One parametrization was found that would fulfill both, tidal deformability and mass-radius constraints. It corresponds to $a_4 = 0.3$, a diquark pairing gap of $\Delta = 120$ MeV and $B_{eff} = 140$ MeV with a low switch function parameter $\mu_0 = 1200$ MeV (see left panels of Figure 2 and 3).

List of References

[1] D. Blaschke, E. -O. Hanu, and S. Liebing. "Neutron stars with crossover to color superconducting quark matter". In: *Phys. Rev. C* 105.3 (2022), p. 035804. DOI: `10.1103/PhysRevC.105.035804`. arXiv: `2112.12145 [nucl-th]`.

[2] N. K. Glendenning. *Compact stars: Nuclear physics, particle physics, and general relativity*. 1997.

[3] J. I. Kapusta and T. Welle. "Neutron stars with a crossover equation of state". In: *Phys. Rev. C* 104.1 (2021), p. L012801. DOI: `10.1103/PhysRevC.104.L012801`. arXiv: `2103.16633 [nucl-th]`.

[4] M. C. Miller et al. "The Radius of PSR J0740+6620 from NICER and XMM-Newton Data". In: *Astrophys. J. Lett.* 918.2 (2021), p. L28. DOI: `10.3847/2041-8213/ac089b`. arXiv: `2105.06979 [astro-ph.HE]`.

Thank you for your attention!