Investigation of the existence of hybrid stars using Nambu-Jona-Lasinio models

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Task Force

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Sumário

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Nambu-Jona-Lasinio Model

- In the present work we consider the NJL Lagrangian in the form

$$\mathcal{L} = \bar{q}(i\gamma^{\mu}\partial_{\mu} - m)q + g_S[(\bar{q}q)^2 + (\bar{q}i\gamma_5\vec{\tau}q)^2] - g_V(\bar{q}\gamma^{\mu}q)^2, \qquad (1)$$

where q is a fermion field with $N_{\mathrm{f}} = 2$ flavors and N_{c} colors. Except for the bare mass m, the Lagrangian is chirally symmetric $\mathrm{SU(2)_L} \times \mathrm{SU(2)_R}$. We included interaction terms in the scalar-isoscalar, pseudoscalar-isovector and vector-isoscalar channels. The g_S and g_V are the scalar and vector couplings, respectively, and they are assumed to be constants with dimensions MeV^{-2}.

- Expanding $\bar{q}q$ and $\bar{q}\gamma^{\mu}q$ we can derive the mean field thermodynamic potential at temperature T and chemical potential μ. We restrict ourselves to the Hartree approximation.

Nambu-Jona-Lasinio Model

- The thermodynamic potential density, Ω, depends on two parameters, namely the dynamical fermion mass, M, and the renormalized quark chemical potential, $\mu_{\rm R}$, which are related to the scalar, $\langle\bar{\psi}\psi\rangle$, and vector, $\langle\psi^\dagger\psi\rangle$, densities at the chemical potential μ through:

$$M = m - 2g_S\langle\bar{\psi}\psi\rangle, \tag{2}$$

$$\mu_R = \mu - 2g_V\langle\psi^\dagger\psi\rangle. \tag{3}$$

These are the NJL gap equations for the dynamical mass and the renormalized chemical potential. The vacuum contribution to the thermodynamic potential density is divergent and has to be regularized. This regularization is performed by introducing a cutoff, Λ. Once we know the thermodynamic potential density, other thermodynamic quantities such as the baryon number density, the energy density and the pressure, can be calculated in the standard way.

Hybrid Stars

J. G. Coelho, C. H. Lenzi, M. Malheiro, R. M. Marinho and M. Fiolhais– IJMPD 19, 1521 (2010)

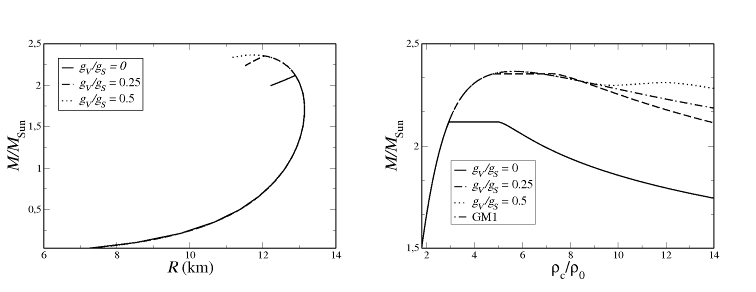


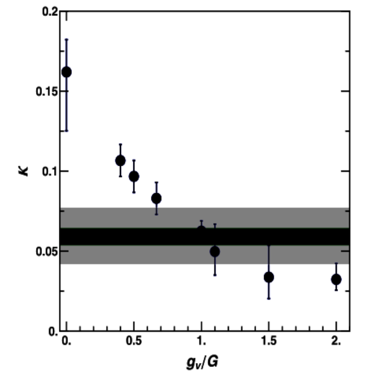
Figure: *Left panel*: Mass-radius diagram obtained with three values for the vector coupling. *Right panel*: Star mass plotted as a function of the central density for different values of the vector coupling.

Hybrid Stars

- for the hadron phase we use the equation of state known as GM1 (Glendenning and Moszkowski) and for the quark phase, we use the mentioned NJL model with vector coupling.
- We observe that the mass is characterized by a "cusp" which is related to an instability.
- the plateau is a consequence of the Gibbs criterium. The width of the plateau is related to the jump in the density at the onset of the quark matter in the interior of the star.
- by increasing the vector coupling, the "cusp" that appears in the mass-radius graph, becomes more tenuous, and the plateau that appears in the mass versus central density plot decreases from $g_V/g_S = 0$ to $g_V/g_S = 0.25$ and even disappears at $g_V/g_S = 0.5$.
- we do not show the effect of higher couplings, because, in that case, the phase transition starts at densities much higher than those considered here ($\rho \leq 10\rho_0$).

N. Bratovic, T. Hatsuda and W. Weise - Physics Letters B 719 (2013) 131–135

Curvature of the crossover boundary in T-u close to $\mu = 0$



1. $\frac{T_c(\mu)}{T_c(0)} = 1 - \kappa \left(\frac{\mu^2}{T_c^2} \right)$
2. or equivalently, $\kappa = -T_c \frac{dT_c(\mu)}{d\mu^2}|_{\mu^2=0}$
3. A recent accurate lattice QCD computation gives $\kappa \sim 0.06$[a].

[a] O. Kaczmarek, F. Karsch, E. Laermann et al. Phys.Rev.D 83 (2011) 014504

Curvature from lattice results is to high comparing with the results obtained in NJL type models without vector interaction ($g_v = 0$).

Increasing g_v implies[1]:

- removing the first-order phase transition turning it to a crossover
- shifting the chiral crossover to regions of larger μ
- flattening of the curvature of smooth crossoverboundary in μ near $\mu = 0$

Curvature lattice results g_v/g_s greather than 0.4. Non local PNJL models $0.5 < g_v/g_s < 0.55$[2].

- larger values of g_v/g_s obtained by making coincide the $T \times \mu$ transition of RMF-PNJL transition with the one of PNJLv, with vector interaction $1.52 \lesssim g_v/g_s \lesssim 3.2$ ($7.66 GeV^{-2} \lesssim g_v \lesssim 16.13 GeV^{-2}$. These values are compatible but restrict the range of $4 GeV^{-2} \lesssim g_v \lesssim 19 GeV^{-2}$, recently obtained from lattice QCD data through a different mean-field model approach[3].

[1] O. Lourenço, M. Dutra, T. Frederico, A. Delfino, M. Malheiro – Phys.Rev.D 84:125034, (2011); Phys.Rev.D 85:097504, (2012).

[2] G. A. Contrera, A. G. Grunfeld and D. B. Blaschke: arXiv:1207.4890.

[3] L. Ferroni and V. Koch, Phys.Rev.C 83, 045205 (2011).

Polyakov-Nambu-Jona-Lasinio models

M. Dutra, O. Lourenco, A. Delfino, T. Frederico, M. Malheiro – Submitted to PRD, (2013)

The mean-field approximation leads to the following grand canonical potential per volume,

$$\begin{aligned}\Omega_{\rm PNJL} &= \mathcal{U}(\Phi,\Phi^*,T) + G_s\rho_s^2 - \frac{\gamma}{2\pi^2}\int_0^\Lambda E\,k^2dk \\ &- \frac{\gamma}{6\pi^2}\int_0^\infty \frac{k^4}{E}dk\,[F(E,T,\mu_q,\Phi,\Phi^*) \\ &+ \bar{F}(E,T,\mu_q,\Phi,\Phi^*)] \end{aligned} \tag{4}$$

where $E = E(M) = (k^2 + M^2)^{1/2}$, ρ_s is the quark condensate given by $\rho_s = \langle\bar{q}q\rangle = \langle\bar{u}u\rangle + \langle\bar{d}d\rangle = 2\langle\bar{u}u\rangle$ in the isospin symmetric system, and $\gamma = N_s \times N_f \times N_c = 12$ is the degeneracy factor due to the spin ($N_s = 2$), flavor ($N_f = 2$), and color numbers ($N_c = 3$). The constituent quark mass is $M = m_0 - 2G_s\rho_s$.

Another difference in the PNJL model is the Polyakov loop potential $\mathcal{U}(\Phi, \Phi^*, T)$. Some versions of this potential were proposed in the literature, we use RRW06[4]. Their functional form is given by,

$$\frac{\mathcal{U}_{\text{RRW06}}}{T^4} = -\frac{b_2(T)}{2}\Phi\Phi^* + b_4(T)\ln\left[h(\Phi, \Phi^*)\right], \tag{5}$$

In order to illustrate the effect of such a modification, we use the Φ dependence on G_s as given by,

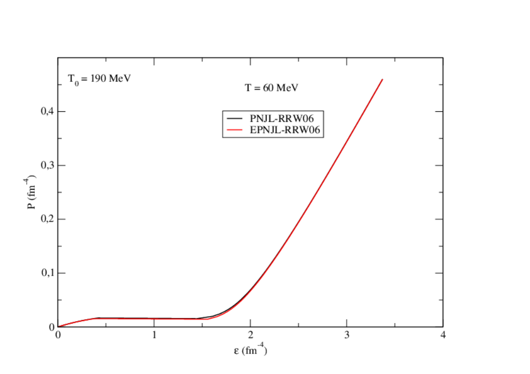
$$G_s(\Phi) = G_s[1 - \alpha_1\Phi\Phi^* - \alpha_2(\Phi^3 + \Phi^{*3})], \tag{6}$$

even concerning the values of $\alpha_1 = \alpha_2 = 0.2$. The PNJL model modified by making $G_s \to G_s(\Phi)$ is named EPNJL model[5], since $G_s = G_s(\Phi)$ is an effective vertex called entanglement vertex.

[4] S. Roessner, T. Hell, C. Ratti, and W. Weise - Nucl.Phys.A **814**, 118 (2008);G. A. Contrera, M. Orsaria, and N. N. Scoccola - Phys.Rev.D **82**, 054026 (2010).

[5] M. Ferreira, P. Costa, D. P. Menezes, C. Providencia, and N. Scoccola, arXiv:1305.4751v1.

Polyakov-Nambu-Jona-Lasinio models



$$\frac{dP}{de} = C_s^2 = (v/s)^2 \sim 0.12 \longrightarrow v/s = 0.35$$

Questions

- Large $g_v/g_s \sim 1$ from Lattice QCD - instability of high Mass Hybrid compact stars in NJL models. How to cure this? Higher order vector-vector or scalar-pseudoscalar terms in NJL?
- We expect confinement-deconfinement transition at high density and zero temperatura, not implemented yet in NJL. How to do that? How to produce effects from confinement at zero temperatura in NJL models? (Polyakov Potential vanishes at $T = 0$). In MIT Bag Model this effect exists: the bag pressure B remains at high densities
- Confinement - chiral condensate strong correlation? New interaction? New versions of entanglement EPNJL

Conclusions

- For $g_V/g_S = 0.5$ we observe that the quark phase shows up right before the second maximum in the plot of the mass versus central density (the small central density range where $\frac{\partial(M/M_{\rm Sun})}{\partial(\rho_c/\rho_0)} > 0$).
- We know that hadronic matter is stable up to the first maximum. The fact that there is a second maximum, means that in a small range of central densities, $\rho_{\rm c}/\rho_0 \sim 9$, the star is stable.
- The smallness of this region indicates that the possibility for stable hybrid stars in NJLv is remote. We conclude that for the phase transition from nuclear to quark matter to take place for larger values of g_V/g_S requires very high central densities, leading to more compact stars.
- Finally, from this study on hybrid stars, we conclude that the use of the NJL model with vector coupling restricts the threshold value for the vector repulsion.

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- undergraduate (120 to 240 students / year) and 50% increase in Graduate (800 to 1200 students).
- new buildings and laboratories.
- In 2014/2015 bulding to accommodate for 600 undergraduate students e 600 graduate students, teachers village to reside within the ITA.