NUCLEAR MATTER EQUATION OF STATE IN RELATIVISTIC MEAN-FIELD THEORY AND MIXED PHASE STRUCTURE IN COMPACT STARS

G.B.Alaverdyan
Yerevan State University, 0025 Yerevan, Armenia

Abstract

The deconfinement phase transition from hadronic matter to quark matter in the interior of compact stars is investigated. The hadronic phase is described in the framework of relativistic mean-field (RMF) theory, when also the scalar-isovector δ-meson effective field is taken into account. The MIT bag model for describing a quark phase is used. The changes of the parameters of phase transition caused by the presence of δ-meson field are investigated. Finally, alterations in the integral and structure parameters of hybrid stars due to deconfinement phase transitions are discussed.

1 Introduction

Study of the structure characteristics and composition of the matter constituents at extremely high density region is of great interest in both nuclear and neutron star physics. The RMF theory [1] has been effectively applied to describe the structure of finite nuclei, the features of heavy-ion collisions, and the equation of state (EOS) of nuclear matter. Inclusion of the scalar-isovector δ-meson in this scheme and investigation of its influence on low density asymmetric nuclear matter was realized in Ref.[2]. At sufficiently high density, different exotic degrees of freedom, such as pion and kaon condensates, also deconfined quarks, may appear in the strongly interacting matter. The modern concept of hadron-quark phase transition is based on the feature of that transition, that is the presence of two conserved quantities in this transition: baryon number and electric charge[3]. It is known that, depending on the value of surface tension, σ_s, the phase transition of nuclear matter into quark matter can occur in two scenarios [4]: ordinary first order phase transition with a density jump (Maxwell construction), or formation of a mixed hadron-quark matter with a continuous variation of pressure and density [3]. Uncertainty of the surface tension values does not allow to determine the phase transition scenario, taking place in realty. In our recent paper [5] in the assumption that the transition to quark matter is a usual first-order phase transition, described by Maxwell construction, we have shown that the presence of the δ-meson field leads to the decrease of transition pressure P_0, of baryon number densities n_N and n_Q. In this article we investigate the hadron-quark phase transition of neutron star matter, when the transition proceeds through a mixed phase. Influence of δ-meson field on such phase transition characteristics and of compact star structure is discussed.

2 Deconfinement phase transition parameters

For description of hadronic phase we use the relativistic Lagrangian density of many-particle system consisting of nucleons, p, n, and exchanged mesons $\sigma,\ \omega,\ \rho,\ \delta$:

$$\mathcal{L}_{\sigma\omega\rho\delta}(\sigma(x),\omega_\mu(x),\vec{\rho}_\mu(x),\vec{\delta}(x))=\mathcal{L}_{\sigma\omega\rho}(\sigma(x),\omega_\mu(x),\vec{\rho}_\mu(x))-U(\sigma(x))+\mathcal{L}_{\delta}(\vec{\delta}(x)),\quad (1)$$

where $\mathcal{L}_{\sigma\omega\rho}$ is the linear part of relativistic Lagrangian density without δ-meson field [6], $U(\sigma)=\frac{b}{3}m_N\left(g_\sigma\sigma\right)^3+\frac{c}{4}\left(g_\sigma\sigma\right)^4$ and $\mathcal{L}_\delta(\vec{\delta})=g_\delta\bar{\psi}_N\vec{\tau}_N\vec{\delta}\psi_N+\frac{1}{2}\left(\partial_\mu\vec{\delta}\partial^\mu\vec{\delta}-m_\delta\vec{\delta}^2\right)$ are the σ-meson self-interaction term and contribution of the δ-meson field, respectively. This Lagrangian density (1) contains the meson-nucleon coupling constants, $g_\sigma,\ g_\omega,\ g_\rho,\ g_\delta$ and also parameters of σ-field self-interacting terms, b and c. In our calculations we take $a_\delta=(g_\delta/m_\delta)^2=2.5$ fm^2 for the δ coupling constant, as in [2, 5]. Also we use $m_N=938.93$ MeV for the bare nucleon mass, $m_N^*=0.78\ m_N$ for the nucleon effective mass, $n_0=0.153$ fm^{-3} for the baryon number density at saturation, $f_0=-16.3$ MeV for the binding energy per baryon, $K=300$ MeV for the incompressibility modulus, and $E_{sym}^{(0)}=32.5$ MeV for the asymmetry energy. Five other constants, $a_i=(g_i/m_i)^2$ $(i=\sigma,\ \omega,\ \rho)$, b and c, then can be numerically determined: $a_\sigma=(g_\sigma/m_\sigma)^2=9.154$ fm^2, $a_\omega=(g_\omega/m_\omega)^2=4.828$ fm^2, $a_\rho=(g_\rho/m_\rho)^2=13.621$ fm^2, $b=1.654\cdot10^{-2}$ fm^{-1}, $c=1.319\cdot10^{-2}$. When we neglect the δ channel, then $a_\delta=0$ and $a_\rho=4.794$ fm^2. The knowledge of the model parameters makes it possible to solve the set of four equations in a self-consistent way and to determine the re-denoted mean-fields, $\sigma\equiv g_\sigma\bar{\sigma}$, $\omega\equiv g_\omega\bar{\omega}_0$, $\delta\equiv g_\delta\bar{\delta}^{(3)}$, and $\rho\equiv g_\rho\bar{\rho}_0{}^{(3)}$, depending on baryon number density n and asymmetry parameter $\alpha=(n_n-n_p)/n$. The standard QHD procedure allows to obtain expressions for energy density $\varepsilon(n,\alpha)$ and pressure $P(n,\alpha)$ [5].

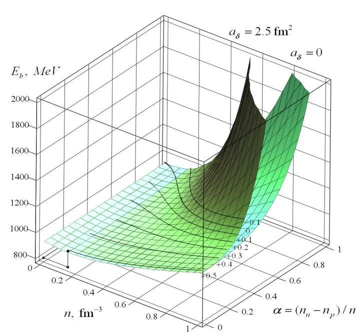

Figure 1: Energy per baryon E_b as a function of the baryon number density n and the asymmetry parameter α in case of a β -equilibrium charged npe-plasma.

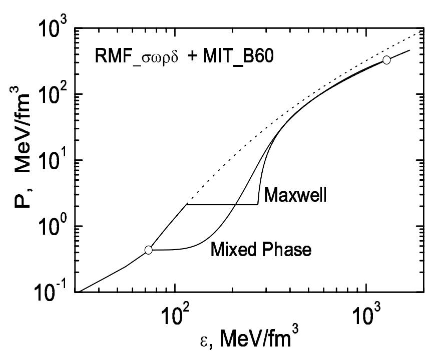

Figure 2: EOS of neutron star matter with deconfinement phase transition.

In Figure 1 we illustrate the 3D-plot of the energy per baryon, $E_b\,(n,\alpha)=\varepsilon_{NM}/n$, as a function of the baryon number density n and asymmetry parameter α in case of a β -equilibrium charged npe-plasma. The curves correspond to different fixed values of the charge per baryon, $q = (n_p - n_e)/n = (1-\alpha)/2 - n_e/n$. The thick one corresponds to β-equilibrium charge neutral npe-matter. The lower and upper surfaces corresponds to the "$\sigma\omega\rho$" and "$\sigma\omega\rho\delta$" models respectively. Clearly, including a δ -meson field increases the energy per baryon, and this change is greater for larger values of the asymmetry parameter. For a fixed value of the specific charge, the asymmetry parameter falls off monotonically as the density is increased. The results of our analysis show that the scalar - isovector δ-meson field inclusion increases the value of the energy per nucleon. This change is strengthened with the increase of the nuclear matter asymmetry parameter, $\alpha = (n_n - n_p)/n$. The δ-field inclusion leads to the increase of the EOS stiffness of nuclear matter due to the splitting of proton and neutron effective masses, and also due to the increase of asymmetry energy (for details see Ref.[7]).

To describe the quark phase an improved version of the MIT bag model is used, in which the interactions between u, d, s quarks inside the bag are taken in a one-gluon exchange approximation [8]. We choose $m_u = 5$ MeV, $m_d = 7$ MeV and $m_s = 150$ MeV for quark masses, $B = 60$ MeV/fm^3 for bag parameter and $\alpha_s = 0.5$ for the strong interaction constant. In Figure 2 we plot the EOS with deconfinement phase transition. The dashed curve corresponds to npe-plasma without any phase transition, while the solid lines correspond to two alternative scenarios of phase transitions. Open circles show the boundary points of the mixed phase. Table 1 represents the parameter sets of the mixed phase both with and without δ-meson field. It is shown that the presence of δ-field alters threshold characteristics of the mixed phase. The lower threshold parameters, n_N, ε_N, P_N are increased, meanwhile the upper ones n_Q, ε_Q, P_Q are slowly decreased.

Table 1: The Mixed phase parameters with and without δ-meson field.

	n_N fm^{-3}	n_Q fm^{-3}	P_N MeV/fm^3	P_Q MeV/fm^3	ε_N MeV/fm^3	ε_Q MeV/fm^3
$\sigma\omega\rho$	0.072	1.083	67.728	1280.889	0.336	327.747
$\sigma\omega\rho\delta$	0.077	1.083	72.793	1280.884	0.434	327.745

In Figure 3 we plot the species number densities as a function of baryon density n. Quarks appear at the critical density $n_N = 0.077$ fm^{-3}. The hadronic matter completely disappears at $n_Q = 1.083$ fm^{-3}, where the pure quark phase occurs. Using the obtained EOS of nuclear matter, we have integrated the Tolman-Oppenheimer Volkoff equations and obtained the mass M and the radius R of compact stars for the different values of central pressure P_c. Figure 4 illustrates the $M(P_c)$ and $R(P_c)$ dependences. The star with maximum mass $M_{max} = 1.853 M_\odot$ corresponds to the central pressure $P_m = 1275.5$ MeV/fm^3, which is less than the upper threshold $P_Q = 1280.884$ MeV/fm^3 is.

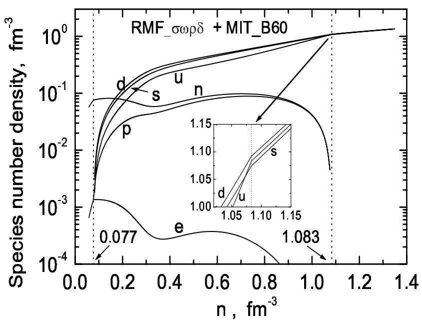

Figure 3: Species number densities vs. baryon number density n.

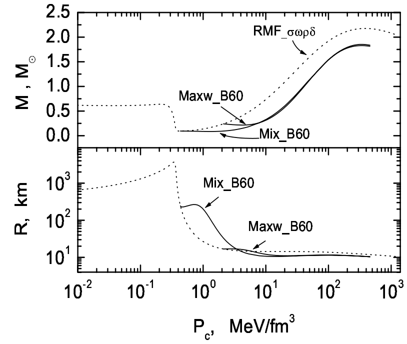

Figure 4: Neutron star Mass M and radius R vs. central pressure P_c.

3 Conclusion

The inclusion of scalar isovector δ-meson field terms leads to the stiff nuclear matter EOS. The presence of δ-meson field alters the threshold characteristics of the mixed phase. The lower threshold parameters, n_N , ε_N , P_N are increased, while the upper thresholds, n_Q , ε_Q , P_Q, are slowly decreased. For EOS used in this study, the central pressure of the maximum mass neutron stars is less than the mixed phase upper threshold P_Q. Thus, the corresponding hybrid stars do not contain pure strange quark matter core.

References

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