A Relativistic Mean Field Theory for Nuclear Matter with σ,δ Meson Couplings at $T \neq 0$

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Abstract. Effects of temperature in hadron dense matter are studied within a generalized relativistic mean field approach based on the naturalness of the various coupling constants of the theory. The lagrangian density of the formulation contains the fundamental baryon octet and nonlinear self interaction components of the σ and δ meson fields coupled to the baryons and to the ω and ρ meson fields. We adjust the model parameters to describe bulk static properties of ordinary nuclear matter and neutron stars, in the framework of the Sommerfeld approximation, at the $T \neq 0$ domain. Through integration of the TOV equations we obtain standard plots for the mass and mass-radius of protoneutron stars as a function of the central density and temperature. Our results indicate an absolute value for the protoneutron star limiting mass at low and intermediate temperature regimes.

EQUATION OF STATE

We pursue our goal — to build an effective field theory for the nuclear many-body problem at finite temperature — through the expansion of a relativistic lagrangian density in terms of the characteristic scales of QCD, within a phenomenological naive dimensional analysis based on the naturalness of the coupling constants of the lagrangian model; our formalism is limited to the scalar sector of the theory[1]. Upon adjusting the model parameters to describe bulk static properties of ordinary nuclear matter, our approach — which represents a *natural* modelling of nuclear matter under the extreme conditions of density and pressure as the ones found in the interior of neutron star — is extended to the $T \neq 0$ domain to describe the structure of protoneutron stars. Our lagrangian density describes a system of eight baryons ($B = p$, n, Λ, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0) coupled to four mesons (σ, ω, ρ, δ) and leptons. Moreover, our approach is based on a derivative coupling model[1] and contains additionally self-coupling contributions of the σ and δ mesons[1]. In order to include trapped neutrinos at chemical equilibrium we followed[2]. The lepton fraction is defined as the ratio $Y_L = \frac{\rho_e+\rho_\nu}{\rho_B}$, where ρ_e, ρ_ν and ρ_B represent the electron, neutrino and baryon densities, respectively. The hyperon/nucleon coupling constant ratios are determined through the binding energy of the Λ-hyperon which correlates the values of the mean-field correlation parameters. We worked with a lepton fraction[1] $Y_l = 0.4$. In the determination of the nuclear matter equation of

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state at finite temperature we have used a set of model parameterizations for which our approach reproduces, for the nucleon effective mass, $M^* = 732 MeV$; for the binding energy of symmetric nuclear matter, $B = -16.3 MeV$; for the compression modulus of nuclear matter, $K = 240 MeV$ and for the symmetry energy coefficient of nuclear matter, $a_4 = 32.5 MeV$, at saturation density, $\rho_f = 0.153\ fm^{-3}$.

We applied standard technical procedures of field theory and the mean-field approximation and obtained an equation of state for nuclear matter as a parametric equation $p = p(\varepsilon)$ which relates the energy density

$$\begin{aligned}\varepsilon &= \frac{1}{2}m_\sigma^2\sigma_0^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 + \frac{1}{2}m_\delta^2\delta_3^2 \\ &+ \sum_B \frac{2J_B+1}{(2\pi)^3}\int_0^\infty \sqrt{k^2+M_B^{*2}}[n(\mu_B,T)+\bar{n}(\mu_B,T)]d^3k \\ &+ \sum_\lambda \frac{2}{(2\pi)^3}\int_0^\infty \sqrt{k^2+m_\lambda{}^2}[n(\mu_\lambda,T)+\bar{n}(\mu_\lambda,T)]d^3k, \end{aligned} \tag{1}$$

and pressure

$$\begin{aligned}p &= -\frac{1}{2}m_\sigma^2\sigma_0^2 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 - \frac{1}{2}m_\delta^2\delta_3^2 \\ &+ \frac{1}{3}\sum_B \frac{2J_B+1}{(2\pi)^3}\int_0^\infty \frac{k^2}{\sqrt{k^2+M_B^{*2}}}[n(\mu_B,T)+\bar{n}(\mu_B,T)]d^3k \\ &+ \frac{1}{3}\sum_\lambda \frac{2}{(2\pi)^3}\int_0^\infty \frac{k^2}{\sqrt{k^2+m_\lambda{}^2}}[n(\mu_\lambda,T)+\bar{n}(\mu_\lambda,T)]d^3k. \end{aligned} \tag{2}$$

In these expressions we can identify scalar-isoscalar and scalar-isovector contributions, followed by vector-isoscalar and vector-isovector terms[1]. Additionally, the effective baryon mass is defined as $M_B^* = M_B - g_\sigma\sigma_0 - g_\delta\delta_3$. In these expressions, the contributions of the Fermi gas of baryons and leptons are represented by sums over the particle families, $B = n, p, \Sigma, \Xi, \Lambda$ and $\lambda = e, \nu$, where J_B is the isospin baryon number. $n(\mu, T)$ and $\bar{n}(\mu, T)$ are the Fermi-Dirac distribution functions for particle and anti-particles, at finite temperature and

$$\mu_i^* = \mu_i - \chi_{\omega i}\frac{g_\omega^2}{m_\omega^2}\rho_B - \chi_{\rho i}I_{3,i}\frac{g_\rho^2}{m_\rho^2}\rho_3. \tag{3}$$

We then combine the Sommerfeld approximation with these expressions[1] and we determine the effects of high density and temperature on the structure of protoneutron stars.

RESULTS AND CONCLUSIONS

The figures show the behavior of the mass-radius relationship and maximum star mass as a function of the central energy density and temperature. Our main result indicates an

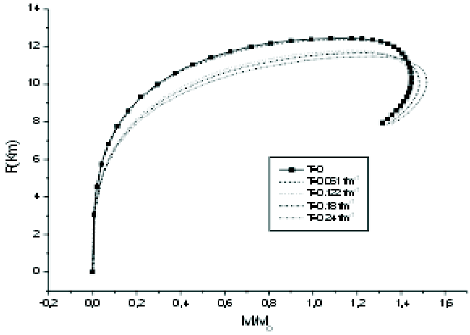

FIGURE 1. Temperature dependence of the mass-radius relationship for protoneutron stars.

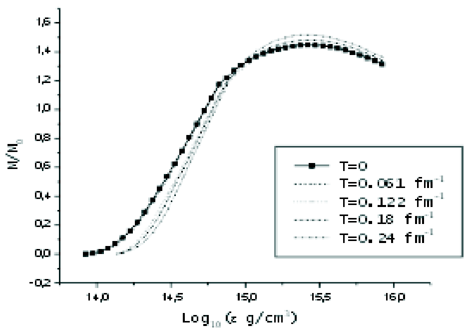

FIGURE 2. Maximum mass for protoneutron star for different values of temperature.

absolute value for the protoneutron star limiting mass at low and intermediate temperature regimes.

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