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Equation of state of hot hyperonic neutron star core

Hristijan Kochankovski,[a,b,*] **Angels Ramos**[b] **and Laura Tolos**[c,d,e]

[a] *Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franquès 1, 08028, Barcelona, Spain*

[b] *Faculty of Natural Sciences and Mathematics-Skopje, Ss. Cyril and Methodius University in Skopje Arhimedova, 1000 Skopje, North Macedonia*

[c] *Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans, 08193 Barcelona, Spain*

[d] *Institut d'Estudis Espacials de Catalunya (IEEC) 08034 Barcelona, Spain*

[e] *Frankfurt Institute for Advanced Studies, Ruth-Moufang-Str. 1 60438 Frankfurt am Main, Germany*

E-mail: hriskoch@fqa.ub.edu, ramos@fqa.ub.edu, tolos@ice.csic.es

A study of the composition and properties of neutron stars and proto-neutron stars is presented, based on a relativistic mean-field model. The baryonic matter equation of state at zero and finite temperatures is computed within the FSU2H* model, which has been updated according to a recent analysis for the Ξ baryon nuclear potential. The finite temperature EoS and composition of matter are computed at constant temperature. It is found that temperature effects are significant and cannot be well reproduced with simple approximations, as the usually adopted Γ - law. This can have a strong impact on the neutron star observables obtained as outputs of complicated relativistic simulations, such as the mass, radius and tidal deformability.

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1. Introduction

Many uncertainties about the equation of state (EoS) and composition of matter under extreme conditions of density and temperature still exist due to the fact that those conditions cannot be reached in terrestrial experiments. Thus, neutron stars emerge as ideal natural laboratories for testing various nuclear matter models under those extreme conditions.

Some models explore the possibility of exotic strange matter appearing at supranuclear densities, that are typical within the neutron star core. However, the number of models that include exotic particles and are extended at finite temperatures is limited. This in fact represents a problem for the complicated relativistic simulations of supernovae explosions and neutron stars mergers that use the equation of state of hot dense matter as an input [1].

In this work we present the FSU2H* model, which is based on the FSU2H scheme [2, 3] but accommodates a recent analysis for the Ξ baryon nuclear potential. We moreover extend the FSU2H* model to finite temperature. Within the model, we study the composition and the equation of state of β^- stable matter that can be found in proto-neutron stars and neutron stars mergers. We also address the problem of using a constant thermal index for obtaining the finite temperature EoS of dense matter, showing that this particular approach can be inaccurate for reproducing the EoS at finite temperature, especially when one considers hyperons in the core of the star.

2. Theoretical framework

We consider hypernuclear matter at a given temperature T, electron lepton number Y_e and baryon density ρ_B, while fixing the muon lepton number to $Y_\mu = 0$. We work within the covariant density functional framework, where one models the interaction between the baryons via the exchange of different mesons. The main quantity that describes the system is the Lagrangian density:

$$\begin{aligned}
\mathcal{L} &= \sum_b \mathcal{L}_b + \mathcal{L}_m + \sum_l \mathcal{L}_l, \\
\mathcal{L}_b &= \bar{\Psi}_b (i\gamma_\mu \partial^\mu - q_b \gamma_\mu A^\mu - m_b + g_{\sigma b}\sigma + g_{\sigma^* b}\sigma^* - g_{\omega b}\gamma_\mu \omega^\mu - g_{\phi b}\gamma_\mu \phi^\mu - g_{\rho,b}\gamma_\mu \vec{I}_b \vec{\rho}^{\,\mu})\Psi_b, \\
\mathcal{L}_m &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{\kappa}{3!}(g_{\sigma b}\sigma)^3 - \frac{\lambda}{4!}(g_{\sigma b})^4 - \frac{1}{4}P^{\mu\nu}P_{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \\
&+ \frac{1}{2}\partial_\mu\sigma^*\partial^\mu\sigma^* - \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} \\
&+ \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{\zeta}{4!}g_{\omega b}^4(\omega_\mu\omega^\mu)^2 - \frac{1}{4}\vec{R}^{\mu\nu}\vec{R}_{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^{\,\mu} + \Lambda_\omega g_{\rho b}^2\vec{\rho}_\mu\vec{\rho}^{\,\mu}g_{\omega b}^2\omega_\mu\omega^\mu, \\
\mathcal{L}_l &= \bar{\Psi}_l\left(i\gamma_\mu\partial^\mu - q_l\gamma_\mu A^\mu - m_l\right)\Psi_l, \qquad (1)
\end{aligned}$$

with $\mathcal{L}_b$ ($b = n, p, \Lambda, \Sigma, \Xi$) representing the baryonic contributions, $\mathcal{L}_m$ being the mesonic term that includes the contributions from the σ, ω, ρ, ϕ and σ^* mesons, and $\mathcal{L}_l$ ($l = e, \mu$ and the corresponding neutrinos) indicating the leptonic terms. With m_i we label the mass of i-th particle, and Ψ_b and Ψ_l are the baryon and lepton Dirac fields, respectively, while $\Omega_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu$, $\vec{R}_{\mu\nu} = \partial_\mu\vec{\rho}_\nu - \partial_\nu\vec{\rho}_\mu$, $P_{\mu\nu} = \partial_\mu\phi_\nu - \partial_\nu\phi_\mu$ and $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ are the mesonic and electromagnetic strength tensors. Lastly, $\vec{I}_b$ is the isospin operator, γ^μ are the Dirac matrices and g_{mb} labels the couplings of the different baryons to the mesons.

Table 1: Parameters of the FSU2H* model. The mass of the nucleon is equal to $m_N = 939$ MeV.

m_σ (MeV)	m_ω (MeV)	m_ρ (MeV)	m_{σ^*} (MeV)	m_ϕ (MeV)	$g^2_{\sigma N}$	$g^2_{\omega N}$	$g^2_{\rho N}$	κ (MeV)	λ	ζ	Λ_ω
497.479	782.500	763.000	980.000	1020.000	102.72	169.53	197.27	4.00014	-0.0133	0.008	0.045

Table 2: The ratios of the couplings of hyperons to mesons with respect to the nucleonic ones.

Y	$R_{\sigma Y}$	$R_{\omega Y}$	$R_{\rho Y}$	$R_{\sigma^* Y}$	$R_{\phi Y}$
Λ	0.6113	2/3	0	0.2812	$-\sqrt{2}/3$
Σ	0.4673	2/3	1	0.2812	$-\sqrt{2}/3$
Ξ	0.3305	1/3	1	0.5624	$-2\sqrt{2}/3$

In order to obtain the EoS and composition of matter one needs to find the equations of motion of the mesons (in the relativistic mean-field approximation), baryons and leptons. Those equations are coupled with the weak equilibrium conditions for the different species:

$$\mu_{b^0} = \mu_n; \;\; \mu_{b^-} = 2\mu_n - \mu_p; \;\; \mu_{b^+} = \mu_p; \;\; \mu_n - \mu_p = \mu_e - \mu_{\nu_e}; \;\; \mu_e = \mu_\mu + \mu_{\nu_e} - \mu_{\bar{\nu}_\mu}, \tag{2}$$

while imposing charge neutrality, and conservation of baryon and lepton density:

$$0 = \sum_{b,l} q_i \rho_i; \;\; \rho_B = \sum_b \rho_b; \;\; Y_l \cdot \rho_B = \rho_l + \rho_{\nu_l}. \tag{3}$$

Note that in the extreme neutrino-free case we have $\mu_{\nu_l} = \mu_{\bar{\nu}_l} = 0$ and the lepton number is no longer a conserved quantity. Then, from the energy-momentum tensor one can extract all thermodynamic quantities of interest. For details, see [4].

In Table 1 we list the values of the parameters of our model for the nuclear sector, whereas in Table 2 we show the additional parameters needed for the hyperonic sector. In particular, the hyperonic couplings to the meson fields are given in terms of their ratios to the corresponding couplings of nucleons: $R_{iY} = g_{iY}/g_{iN}$ for $i = (\sigma, \omega, \rho)$, and $R_{\sigma^* Y} = g_{\sigma^* Y}/g_{\sigma N}$ and $R_{\phi Y} = g_{\phi Y}/g_{\omega N}$, since $g_{\sigma^* N} = 0$ and $g_{\phi N} = 0$ due to the OZI (Okubo-Zweig-Iizuka) rule.

3. Results

3.1 Composition and EoS

In Fig. 1 we show the composition (left graph) and EoS (right graph) for β^- equilibrated matter at two different temperatures ($T = 5$ MeV and $T = 50$ MeV) and different leptonic fraction (ν_e free matter and $Y_l = 0.4$). In order to see the effect of the appearance of hyperons we show our results without (solid lines) and with (dashed lines) hyperons.

From the left graph of Fig. 1 we can see that the composition shows a stronger density dependence when hyperons are present in the core. However, their abundance depends on the temperature and the leptonic fraction of the core. When the temperature is low, hyperons appear at densities around $\rho_B = 0.38$ fm^{-3}. This is not the case at high temperatures, where hyperons are present at any point of the core of the star. One can also notice that their contribution is more

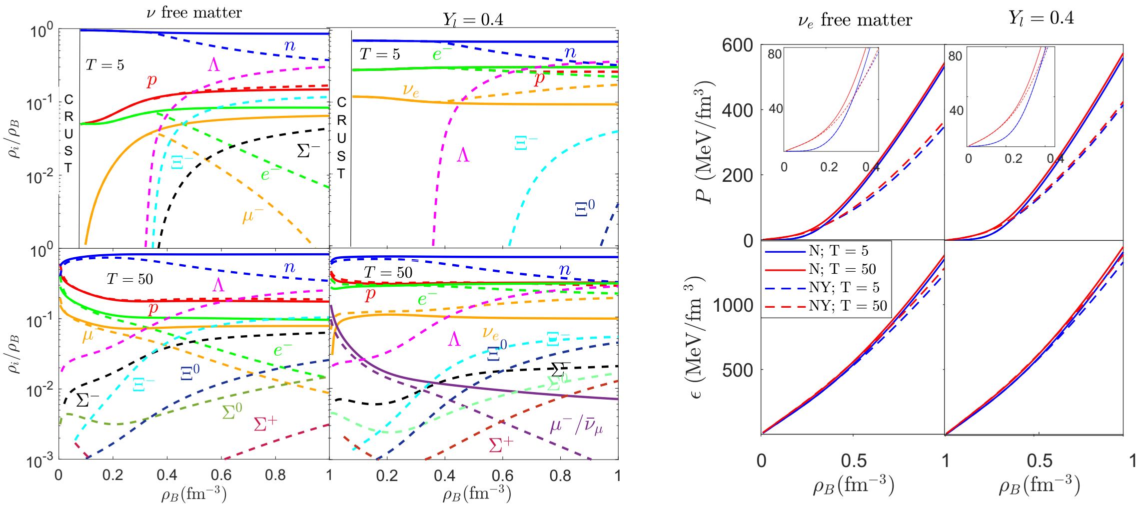

Figure 1: Composition (left) and EoS (right) as a function of the baryon density for matter in β^- equlibrium for both neutrino free and neutrino trapped (Y_l) scenarios. The dashed lines correspond to cases where hyperons are taken into account while solid lines represent nucleonic-only cases. The calculations are done for two temperatures (T = 5 MeV and T = 50 MeV)

important when neutrinos are already diffused from the star. In that case, when hyperons start to appear in the core, a deleptonization process takes place and the leptons slowly disappear. However, when neutrinos are trapped in the core of the star, the lepton number is conserved, so the abundance of hyperons is hindered.

As in the case of the composition, the EoS is also affected by the presence of hyperons in the core. As seen on the right graph of Fig. 1 this is especially noticeable if one looks at the pressure, which is significantly lower in the hyperonic case leading to a softening of the equation of state. The energy density is also lower when hyperons are present in the core, but this effect is less evident. One can also notice that temperature effects on the EoS are more important at lower densities. At higher densities, matter becomes degenerate and these effects start to fade.

3.2 Thermal index

Due to the reduced number of finite temperature EoS models, many numerical simulations of supernovae and mergers resort to approximations that provide the finite temperature EoS from the corresponding one at zero temperature. One usual approach is inspired by the Γ-law, that is, $P_{th} = \epsilon_{th}(\Gamma - 1)$. For a diluted ideal non-relativistic gas the Γ-law connects the thermal pressure ($P_{th}(T) = P(T) - P(T = 0)$) and the thermal energy ($\epsilon_{th}(T) = \epsilon(T) - \epsilon(T = 0)$) with $\Gamma = 5/3$. Hence, many groups obtain the finite temperature EoS in an analogous way, assuming that the Γ index is constant for all densities and temperatures and takes a value between 1.5 and 2.

In order to investigate whether this approach is valid, in the left panel of Fig. 2 we show the thermal index for neutrino free matter as a function of ρ_B, whereas in the right panel we display the thermal pressure as a function of thermal energy for the nucleonic (solid lines) and hyperonic (dashed lines) cases. It is clear that the thermal index shows a clear dependence with density and temperature and its deviation from a constant behavior is even worse when hyperons are taken into account. One can notice that the sudden drop that thermal index experiences corresponds to the density in the core at which the hyperonic abundance becomes significant. Since the appearance of the hyperons is softer as the temperature increases, the drop is also shallower at higher temperatures. The complex behaviour of Γ is also clearly visible in the $P_{th}(\epsilon_{th})$ plane, as seen on the right panel of Fig 2. From that panel it is easy to conclude that a constant Γ factor would not reproduce the thermal effects of the EoS with satisfactory accuracy.

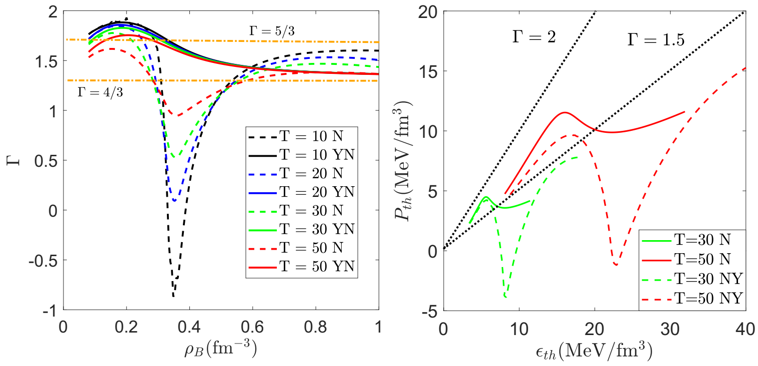

Figure 2: Left panel: Thermal index as a function of baryon density. Right panel: thermal pressure as a function of thermal energy. Solid lines lines correspond to the cases where hyperons are not considered in the core of the star, while dashed lines represent calculations where hyperons are taken into account.

4. Conclusion

We have constructed the new FSU2H* model for the core of neutron stars and used it for β^- equilibrated matter at finite temperature. Within the model, we have investigated the composition and EoS of neutron star cores and found them to be substantially modified by the appearance of hyperons. We have also analyzed the thermal energy and pressure of the matter, concluding that the Γ law for obtaining the finite temperature EoS can inaccurately reproduce the thermal effects in numerical simulations of supernovae and neutron star mergers.

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