An equation of state for magnetized neutron star matter and tidal deformation in neutron star mergers

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Abstract

We derive an equation of state (EoS) for magnetized charge-neutral nuclear matter relevant for a neutron star (NS). The calculations are performed within an effective chiral model based on the generalization of the σ model with nonlinear self-interactions of the σ mesons along with the $\rho - \sigma$ cross-coupling term. This model is extended by introducing the contributions of a strong magnetic field on the charged particles. The resulting EoS for the magnetized dense matter is used to investigate the NS properties like its mass, radius, and tidal deformability. The magnitude of the magnetic field at the core of the NS considered here is in the range of 10^15˘10^18 G, for which the relative deformation from spherical symmetry turns out to be less than 1%, giving a post facto justification for the spherically symmetric treatment of the NS structure.

Methodology

The effective Lagrangian of the model interacting through the exchange of the pseudo-scalar meson π, the scalar meson σ, the vector meson ω and the iso-vector $\rho-$meson is given by

$$\begin{aligned}\mathcal{L} &= \sum_B \bar{\psi}_B \left[\left(i\gamma_\mu\partial^\mu - g_{\omega B}\partial_\mu\omega^\mu - \frac{1}{2}g_{\rho B}\vec{\rho_\mu}\cdot\vec{\tau}\gamma^\mu\right) - g_{\sigma B}\left(\sigma + i\gamma_5\vec{\tau}\cdot\vec{\pi}\right)\right]\psi_B + \frac{1}{2}\left(\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} + \partial_\mu\sigma\partial^\mu\sigma\right) \\ &-\frac{\lambda}{4}(x^2-x_0^2)^2 - \frac{\lambda B}{6}(x^2-x_0^2)^3 - \frac{\lambda C}{8}(x^2-x_0^2)^4 - \frac{1}{4}F_{\mu\nu}F_{\mu\nu} + \frac{1}{2}g_\omega^2 x^2\omega_\mu\omega^\mu - \frac{1}{4}\vec{R_{\mu\nu}}\cdot\vec{R^{\mu\nu}} \\ &+\frac{1}{2}m_\rho'^2\vec{\rho_\mu}\cdot\vec{\rho^\mu} + \eta_1\left(\frac{1}{2}g_\rho^2 x^2\vec{\rho_\mu}\cdot\vec{\rho^\mu}\right) + \eta_2\left(\frac{1}{2}g_\rho^2 x^2\rho_\mu\cdot\rho^\mu\omega_\mu\omega^\mu\right). \qquad (1)\end{aligned}$$

The energy density and the pressure of the considered model is given by,

$$\begin{aligned}\epsilon &= \frac{1}{\pi^2}\sum_{i=n,p}\int_0^{k_F^i} k^2\sqrt{k^2+m^{\star 2}}dk + \frac{m^2}{8C_\sigma}(1-Y^2)^2 - \frac{b}{12C_\sigma C_\omega}(1-Y^2)^3 + \frac{c}{16m^2C_\sigma C_\omega^2}(1-Y^2)^4 + \frac{1}{2}m_\omega^2\omega_0^2Y^2 \\ &+\frac{1}{2}m_\rho^2\Big[1-\eta_1(1-Y^2)(C_\rho/C_\omega) + 3\eta_2 C_\rho\omega_0^2\Big](\rho_3^0)^2, \qquad (2)\end{aligned}$$

$$\begin{aligned}p &= \frac{1}{3\pi^2}\sum_{i=n,p}\int_0^{k_F^i}\frac{k^4}{\sqrt{k^2+m^{\star 2}}}dk - \frac{m^2}{8C_\sigma}(1-Y^2)^2 + \frac{b}{12C_\sigma C_\omega}(1-Y^2)^3 - \frac{c}{16m^2C_\sigma C_\omega^2}(1-Y^2)^4 + \frac{1}{2}m_\omega^2\omega_0^2Y^2 \\ &+\frac{1}{2}m_\rho^2\Big[1-\eta_1(1-Y^2)(C_\rho/C_\omega) + \eta_2 C_\rho\omega_0^2\Big](\rho_3^0)^2. \qquad (3)\end{aligned}$$

The energy density and pressure in the present model in presence of external magnetic field are given by

$$\epsilon = \epsilon_n + \epsilon_p + \epsilon_{meson} + \frac{1}{2}B^2 \qquad (4)$$

$$.P = P_n + P_p - \epsilon_{meson} - \frac{1}{2}B^2 \equiv P_0 - \frac{1}{2}B^2. \qquad (5)$$

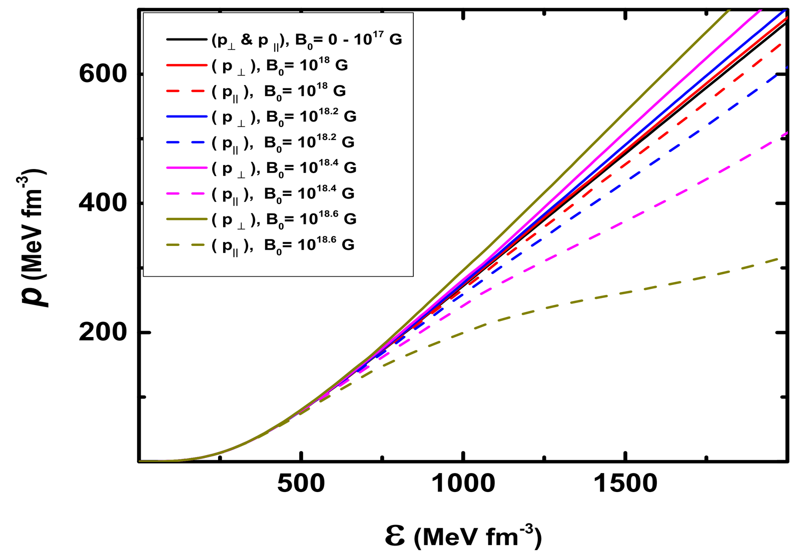
$$\text{Where, } B(\mu) = B_{surf} + B_0\left(1 - e^{\left(\frac{-b(\mu-938)^a}{938}\right)}\right) \qquad (6)$$

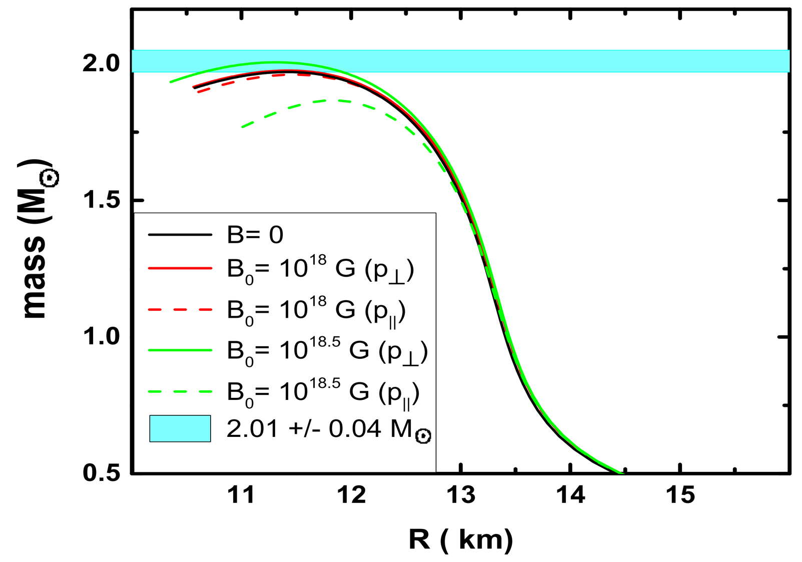
The inputs for our calculations are given in the below table

Table 1

C_σ fm^2	C_ω fm^2	C_ρ fm^2	η_1	B fm^2	C fm^4
7.057	1.757	12.28	-0.79	-5.796	0.001
ρ_0	$m^\star$	K	e_0	J_0	L_0
0.153	0.86	247	-16.0	32.5	65

Results





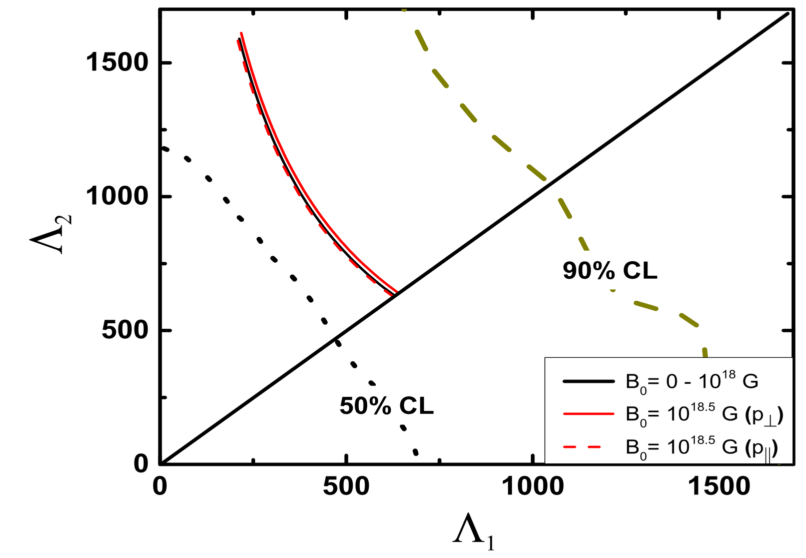


Figure 1. we show the EoS of the magnetized charged neutral matter for different strengths of the core magnetic field B_0. Beyond 10^{18} G, the difference between these two pressures increases rapidly. The perpendicular component becomes stiffer while the parallel component becomes softer.

Figure 2. We find that there is no appreciable change in the gravitational mass and radius of the NS when magnetic effects are incorporated for fields straight up to $B_0 = 10^{17}$G compared to the case where the magnetic field is absent.

Figure 3. The curves are obtained by varying the high mass (M 1)independently in the range $1.365 < M/M_\odot < 1.60$ obtained for GW 170817 whereas the low mass (M2) is determined by keeping the chirp mass fixed at the observed value of 1.188 $M_\odot$. We observed from the figure, the EOS obtained from the present chiral model for nucleon matter lies well within the two limits with or without the magnetic field.

Table 2

B_0 (Gauss)	M ($M_\odot$)	R (km)	$R_{1.4}$ (km)
0	1.97	11.42	13.11
$10^{15} - 10^{17}$ ($\perp$)	1.97	11.43	13.13
($\parallel$)	1.97	11.43	13.13
10^{18} ($\perp$)	1.97	11.43	13.14
($\parallel$)	1.96	11.47	13.13
$10^{18.5}$ ($\perp$)	2.01	11.30	13.15
($\parallel$)	1.87	11.83	13.12

Conclusion

The nuclear symmetry energy, as well as its slope and curvature parameters at ρ_0, are in deduced from a diverse set of experimental data, and the obtained maximum mass of the NS is $1.97 M_\odot$, which is the lower bound of the observed NS of mass 2 $M_\odot$

Future Work

The inclusion of hyperons in this model will further reduce the maximum NS mass irrespective of the choice of the hyperon coupling constant.