Exotic Equation of State Compatible With Two Solar Mass Neutron Star Observation

Prasanta Char[1*] and Sarmistha Banik[2]
[1] *Astroparticle Physics & Cosmology Division, Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700 064, India and*
[2] *BITS Pilani, Hyderabad Campus, Samirpet Mondal, Hyderabad 500078, India*

Introduction

Neutron Stars are the densest objects known in the observable universe. The recent measurement of $1.97 \pm 0.04 M_{solar}$ for PSR J1614-2230 [1] in 2010 and $2.01 \pm 0.04 M_{solar}$ for PSR J0348+0432 [2] in 2011 puts a strong constraint on the neutron star equation of state (EoS) and its composition at higher densities. Pauli exlusion principle dictates the appearance of strange degrees of freedom in the high density baryonic matter. Presence of strange hadrons (hyperons and kaons) may result in a softer EoS that on the other hand corresponds to a neutron star of mass lower than $2M_{solar}$. These models are ruled out by the recent observations. Various attempts to model neutron star matter containing exotica compatible with the $2M_{solar}$ benchmark have been proposed. We use density dependent relativistic mean field (RMF) model in this study [3–6], which aims to investigate the possibility of constructing an EoS with strange matter and achieve a maximum mass within the observable limit of $2M_{solar}$.

Formalism

In our approach, the model Lagrangian density ($\mathcal{L} = \mathcal{L}_B + \mathcal{L}_l$) is of the form

$$\begin{aligned}\mathcal{L}_B = &\sum_{B=N,\Lambda,\Sigma,\Xi} \bar{\psi}_B(i\gamma_\mu\partial^\mu - m_B + g_{\sigma B}\sigma \\ &- g_{\omega B}\gamma_\mu\omega^\mu - g_{\rho B}\gamma_\mu \boldsymbol{\tau}_B \cdot \boldsymbol{\rho}^\mu)\psi_B \\ &+ \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} \\ &+ \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\boldsymbol{\rho}_{\mu\nu}\cdot\boldsymbol{\rho}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu.\end{aligned}$$

Leptons are, as non-interacting particles, described by $\mathcal{L}_l = \sum_l \bar{\psi}_l \left(i\gamma_\mu\partial^\mu - m_l\right)\psi_l$. The $g_{\alpha B}(\hat{n})$'s, where $\alpha = \sigma,\ \omega$ and ρ are vector density-dependent. Interaction among hyperons are mediated by additional vector meson $\phi(1020)$. The Lagrangian density for (anti)kaons in the minimal coupling scheme is given by

$$\mathcal{L}_K = D_\mu^* \bar{K} D^\mu K - m_K^{*2}\bar{K}K \ ,$$

where the covariant derivative is $D_\mu = \partial_\mu + ig_{\omega K}\omega_\mu + ig_{\rho K}\boldsymbol{\tau}_K \cdot \boldsymbol{\rho}_\mu + ig_{\phi K}\phi_\mu$ and $m_K^* = m_K - g_{\sigma K}\sigma$. In the mean field approximation, the meson field equations are solved self consistently in the presence of antikaon condensates.

In the Dirac equation, a rearrangement term appears in the usual vector self energy part, and is given by, $\Sigma_B^{(r)} = \sum_B[-g'_{\sigma B}\sigma n_B^s + g'_{\omega B}\omega_0 n_B + g'_{\rho B}\tau_{3B}\rho_{03}n_B + g'_{\phi B}\phi_0 n_B]$, where $g'_{\alpha B} = \frac{\partial g_{\alpha B}}{\partial \rho_B}$, $\alpha = \sigma,\ \omega,\ \rho,\ \phi$ and τ_{3B} is the isospin projection. The chemical potential for the baryon B is $\mu_B = \sqrt{k_B^2 + m_B^{*2}} + g_{\omega B}\omega_0 + g_{\rho B}\tau_{3B}\rho_{03} + g_{\phi B}\phi_0 + \Sigma_B^{(r)}$. The energy density and presssure are calculated using the prescription given by eq. 30 and 31 of Ref. [4].

Parameters

We employ DD2 model considering the importance of the nuclear symmetry energy to determine the behaviour of the EoS at high densities. The symmetry energy and its slope parameters associated with the DD2 model are fully consistent with experimental constraints [7]. Parameters of the density-dependent meson-nucleon couplings in DD2 model are taken from Ref. [6]. The functional dependence of the couplings on density is described as $g_{\alpha B}(n_b) = g_{\alpha B}(n_0)f_\alpha(x)$, where n_b is the total baryon density, $x =$

*Electronic address: `prasanta.char@saha.ac.in`

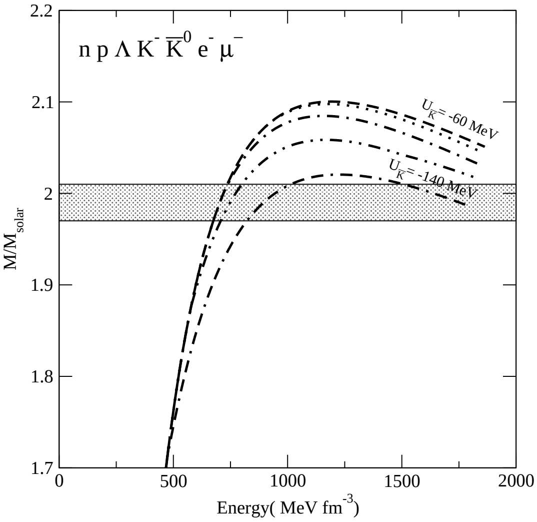

FIG. 1: Neutron star mass sequences are plotted with central energy density for antikaon potential depths $U_{\bar{K}}(n_0)$= -60,-80,-100,-120 and -140 MeV. Deeper $U_{\bar{K}}$ corresponds to lower line. The gray band specifies the observational limits

n_b/n_0, and $f_\alpha(x) = a_\alpha \frac{1+b_\alpha(x+d_\alpha)^2}{1+c_\alpha(x+d_\alpha)^2}$ is taken for $\alpha = \omega$, σ. For the isovector meson ρ, $f_\alpha(x) = \exp[-a_\alpha(x-1)]$.

The vector coupling constants for hyperons are determined from the SU(6) symmetry [8]. The scalar meson (σ) coupling to hyperons is obtained from the potential depth of a hyperon (Y) in the saturated nuclear matter $U_Y^N(n_0) = -g_{\sigma Y}\sigma + g_{\omega Y}\omega_0 + \Sigma_N^{(r)}$, We compute the meson-anti(kaon) couplings from the quark model and isospin counting rule And $g_{\sigma K}$ is obtained from K^- optical potential $U_{\bar{K}}(n_0) = -g_{\sigma K}\sigma - g_{\omega K}\omega_0 + \Sigma_N^{(r)}$.

Results

We report the result of our calculations using DD2 model. We construct the EoS with hyperons for the antikaon optical potential depths $U_{\bar{K}}(n_0)$= -60,-80,-100,-120 and -140 MeV. The EoS starts to soften once strange degrees of freedom appears. For static neutron stars we solve the TOV equation for the above mentioned EoSs. For low denisty crust we used the results of BPS model [9]. We found the maximum mass of a nucleon-only star to be $2.417M_{solar}$. The static star sequences and the corresponding central energy densities are plotted in 1 for n, p, Λ, and lepton matter with K^- and $\bar{K}^0$ condensates for different values of $U_{\bar{K}}(n_0)$. The softening of EoS results in decrease in maximum mass. The maximum mass of the star varies from $2.10M_{solar}$ [for $U_{\bar{K}}(n_0)$= -60 MeV] to $2.02M_{solar}$ [for $U_{\bar{K}}(n_0)$= -140 MeV]. At deeper potential, the threshold of $\bar{K}$ condensation shifts to lower density, therefore increasing the $\bar{K}$ fraction and further softening the EoS.

Summary

We have used the DD2 model parameters from Typel et. al [6] to contruct the EoS of the dense matter relevant to compact star core. We have also taken ϕ meson as a mediator of repulsive interaction between hyperons. We observe that the strangeness degrees of freedom softens the EoS and lowers the maximum mass. However, in all cases we find the maximum mass within the constraint of observable limits. So, we argue that exotic EoS may not be ruled out altogether by the observation of a $2M_{solar}$ pulsar.

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