Limiting mass of fastest spinning neutron stars

Ankit Kumar,* Abhishek, Swati Modi,† and P. Arumugam
Department of Physics, Indian Institute of Technology Roorkee, Roorkee - 247 667, India

Introduction

Neutron stars are rapidly rotating remnant cores of massive stars (with mass 1.5 to 3 times the mass of sun) that undergo supernovae explosions. Fast spinning neutron stars with a period of a few milliseconds are called millisecond pulsars (MSPs). Large centrifugal forces tend to deform these stars into oblate spheroids. In this work, we have solved the Einstein field equations in an axially symmetric space-time to calculate various properties of rapidly rotating neutron stars. The interactions in the dense matter are modelled with the Covariant Density Functional Theory (CDFT). Apart from causality, we have constrained the model equation of states (EoSs) with the neutron star size limits suggested by the recent gravitational wave observations. By imposing a statistical cut-off on pulsar spin, we estimated the maximum mass of the fastest MSP sequence.

Formalism

The effective mean-field Lagrangian density of nuclear matter ignoring electromagnetic contribution reads [1–3]

$$\begin{aligned}
\mathcal{L} &= \sum_B \bar{\psi}_B[\gamma^\mu \left(-g_{\omega B}V_\mu - g_{\rho B}\ \vec{\tau}_B.\vec{R}_\mu\right) \\
&- (m_B - g_{\sigma B}\sigma)]\psi_B + \sum_l \bar{\psi}_l\left(-m_l\right)\psi_l \\
&- \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2 V_\mu V^\mu + \frac{1}{2}m_\rho^2\vec{R}_\mu.\vec{R}^\mu \\
&+ \frac{\zeta_0 g_{\omega N}^2}{4!}(V_\mu V^\mu)^2 + \Lambda_v g_{\omega N}^2 g_{\rho N}^2 V_\mu V^\mu \vec{R}_\mu.\vec{R}^\mu \\
&- m_\sigma^2\sigma^2\left(\frac{\kappa_3}{3!}\frac{g_{\sigma N}\sigma}{m_n} + \frac{\kappa_4}{4!}\frac{g_{\sigma N}^2\sigma^2}{m_n^2}\right), \qquad (1)
\end{aligned}$$

where the symbols carry their usual meanings. Assuming all hyperons interact similarly with the meson fields, we quantify their interactions by the ratios

$$x_\sigma = \frac{g_{\sigma H}}{g_{\sigma N}},\ x_\omega = \frac{g_{\omega H}}{g_{\omega N}},\ \text{and}\ x_\rho = \frac{g_{\rho H}}{g_{\rho N}}, \quad (2)$$

where $H \in \{\Sigma, \Xi, \Lambda\}$, and N denotes the nucleons. Assuming $x_\rho = x_\sigma$, x_ω is given by

$$x_\omega = \frac{x_\sigma g_{\sigma N}\sigma_0(\rho_0) + U_\Lambda(\rho_0)}{g_{\omega N}V_0(\rho_0)}, \quad (3)$$

where ρ_0 is the nuclear saturation density and $U_\Lambda(\rho_0) = -28$ MeV is the Λ potential depth in normal nuclear matter. Various studies on hypernuclear energy levels together with recent observations of massive pulsars with $M \approx 2\ M_\odot$ (where $M_\odot$ is the solar mass) suggest $0.7 \lesssim x_\sigma \lesssim 0.8$. The kaon field is incorporated using the minimal coupling scheme by

$$\mathcal{L}_K = D_\mu^* K^* D^\mu K - m_K^{*2} K^* K, \quad (4)$$

where D_μ $(= \partial_\mu + ig_{\omega K}V_\mu + ig_{\rho K}\vec{\tau}_B.\vec{R}_\mu)$ is the covariant derivative, and m_K^* is the in-medium kaon mass. The antikaon interaction is quantified by the kaon optical potential, which typically lies in the range $-180 \lesssim U_K(\rho_0) \lesssim -80$ MeV. The kaon-meson interactions are calculated using

$$g_{\omega K} = g_{\omega N}/3, \quad (5)$$

$$g_{\rho K} = g_{\rho N}/2, \quad (6)$$

$$g_{\sigma K} = -\frac{g_{\omega K}V_0(\rho_0) + U_K(\rho_0)}{\sigma_0(\rho_0)}. \quad (7)$$

The energy density and pressure (ϵ and p) are calculated from the diagonal elements of energy-momentum tensor ($T^{\mu\nu}$) by

$$\epsilon = T^{00},\ \text{and}\ p = \frac{1}{3}\sum_{j=1,2,3} T^{jj} \quad (8)$$

*Electronic address: akvyas1995@gmail.com
†Currently at Department of Physics, Birsa Institute of Technology Sindri, Sindri - 828 123, India

Results and discussions

The observed properties of massive neutron stars with $M \approx 2\ M_\odot$ have been widely used for constraining the nuclear matter EoS. With a mass of $2.01 \pm 0.04\ M_\odot$ and a negligible rotation frequency of 25 Hz, PSR J0348+0432 is the most massive pulsar detected till date. In this work, we assume that the limiting mass of non-rotating neutron star sequence $M_{TOV} = 2.05\ M_\odot$. Using the recently proposed FSU2H parametrisation of the Lagrangian density, we have investigated the existence of hyperons (FSU2Hh) and the coexistence of hyperons with antikaons (FSU2Hhk) inside a neutron star. The hyperon and antikaon interactions are adjusted so that the assumption $M_{TOV} = 2.05\ M_\odot$ holds true. The existence of strange species in neutron star cores cannot be ruled out by any available data as our model EoSs satisfy

1. The kinetic theory constraint on the speed of sound (c_s), which in natural units is given by [4]

$$c_s < \sqrt{\frac{\epsilon - p/3}{\epsilon + p}}. \tag{9}$$

2. The constraint on neutron star radius (R) suggested from analysis of various high energy astronomical observations ($R \lesssim 13$ km for $M \approx 2\ M_\odot$) [2].

3. The gravitational wave constraint on the radius of a normal neutron star ($R \leq 13.76$ km for $M = 1.4\ M_\odot$) [7].

Even after the inclusion of strange species, both EoSs violate the causal limit of QCD ($c_s < 1/\sqrt{3}$). If we demand the EoSs to satisfy the above limit, the existence of PSR J0348+0432 cannot be explained. Similar inconsistencies have been reported in Ref. [8]. Fig. 1 represents the percentage increase in limiting mass (ΔM_{lim}) with pulsar spin (ν). The existence of a spin cut-off is strongly suggested by an observational absence of sub-millisecond pulsars. The competing theories for explaining the same are the onset

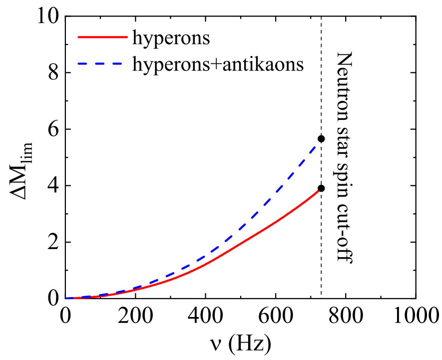

FIG. 1: Spin dependence of MSP limiting mass. ν is the rotation frequency and ΔM_{lim} is the percentage increment in maximum mass over M_{TOV}. The vertical dashed line represents the pulsar spin cut-off at $\nu_{max} = 730$ Hz.

of unstable r-mode oscillations, and the enhanced emission of electromagnetic waves beyond some critical frequency. The best statistical estimate of this boundary between stable and unstable rotation is $\nu_{max} = 730$ Hz [6], which is the maximum frequency set in Fig. 1. For such a fast spinning neutron star sequence, the increment in limiting mass is $\approx 4\%$ with hyperons and $\approx 6\%$ with coexisting hyperons and antikaons.

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