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Hyperons and massive neutron stars: Vector repulsion and strangeness

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Abstract

Finding the composition of cold dense matter is still a serious challenge. Recent neutron star observations, especially the observed mass of pulsar PSR J1614-2230 with $M = (1.97 \pm 0.04)\ M_\odot$, constrain the equation of state (EoS) of hadronic matter and question the existence of hyperons in the core of neutron stars. As in previous work, we investigate the conditions for the presence of hyperons in the neutron star core by exploring the vector baryon–meson coupling assuming flavor SU(3) symmetry. However, as an extension to our work, we investigate the full range of SU(3) parameters which had previously been kept fixed.

Keywords: Neutron stars; Equation of state; Hypernuclei; Hadronic matter

1. Introduction

The core of a massive neutron star such as the millisecond pulsar PSR J1614-2230 with an observed mass of $1.97 \pm 0.04\ M_\odot$ [1] provides a realisation of cold matter at several times nuclear matter saturation density. Since any theory of dense matter has to be able to explain such a massive neutron star, the observed mass of PSR J1614-2230 helps to constrain the equation of state (EoS) of matter beyond nuclear saturation density. In existing models, the appearance of

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hyperons in hadronic matter is found to drastically soften the EoS resulting in a smaller maximum mass of neutron stars. Therefore, large observed neutron star masses seem to contradict existing models of dense matter including hyperons (see e.g. Refs. [2,3]).

While many models including hyperons yield maximum masses smaller than $1.97 \pm 0.04 M_\odot$ there is also a number of studies which have found maximum masses compatible with PSR J1614-2230 (see e.g. Refs. [4–6] and references therein; see also Ref. [7] for a more detailed list of references). In these cases, a stiffening of the EoS is obtained by shifting the threshold for the appearance of hyperons to higher densities or by increasing the vector repulsion between hyperons in what often seems an ad hoc way. In a recent work, we have chosen a different way based on symmetry arguments [7]. For the description of baryon interaction we have adopted flavor SU(3) symmetry. Further, we have made use of a relativistic mean field (RMF) model with parameters calibrated near saturation density [8–10]. In order to extend this model to high densities, we have relaxed the assumption of SU(6) symmetry relating the hyperon couplings to the nuclear couplings. Instead we have assumed the more general SU(3) symmetry and have performed a controlled parameter study in order to investigate the influence of the SU(3) parameters on the existence of hyperons in massive neutron stars. As an extension to our previous work we now complete the parameter study going to more general configurations.

2. Theoretical model

For the description of charge neutral baryonic matter in chemical equilibrium we follow our recent studies [7,11] and assume an RMF model [10] incorporating electrons, muons and the full $J^P = \frac{1}{2}^+$ baryon octet as constituents of the neutron star core. The interaction between baryons is mediated by the exchange of scalar (σ), vector (ω) and isovector (ρ) mesons. Additionally, the strange scalar (σ^*) and strange vector (ϕ) mesons account for hyperon–hyperon interactions. In this model, the EoS becomes stiffest if the σ^* is omitted but the ϕ included. This choice is referred to as "model $\sigma\omega\rho\phi$" [7,11]. Since the presence of the σ^* would lower the maximum mass, our studies will provide an upper limit on the parameters of the model. It was shown in Ref. [12] that the σ^* increases the strangeness per baryon of neutron stars. Our analysis will therefore yield a lower bound on the stars' strangeness content. As in our previous study [7], the couplings of the ω and ϕ mesons to hyperons are related to the corresponding nucleon couplings not by the symmetry of the SU(6) quark model but by the more general SU(3) symmetry. Assuming a flavor SU(3) invariant interaction between the baryons and the ω and ϕ mesons leads to relations between the corresponding coupling constants by means of only four parameters: the meson singlet and octet coupling constants g_1 and g_8, the so-called mixing angle θ and the F/(F + D) ratio α_V, weighting the symmetric (D) and the antisymmetric (F) part of the octet interaction [13]. The angle θ is fixed by the condition of ideal mixing, $\tan\theta = 1/\sqrt{2}$ [14]. Since we fit the nucleon–ω coupling to saturation properties of nuclear matter, we trade g_8 and g_1 for $g_{N\omega}$ and $z = g_8/g_1$ and obtain the following relative coupling strengths:

$$\frac{g_{\Lambda\omega}}{g_{N\omega}} = \frac{\sqrt{6} - 2(1-\alpha_V)z}{\sqrt{6} + (4\alpha_V - 1)z}, \qquad \frac{g_{\Sigma\omega}}{g_{N\omega}} = \frac{\sqrt{6} + 2(1-\alpha_V)z}{\sqrt{6} + (4\alpha_V - 1)z}$$

$$\frac{g_{\Xi\omega}}{g_{N\omega}} = \frac{\sqrt{6} - 2(1+2\alpha_V)z}{\sqrt{6} + (4\alpha_V - 1)z}, \qquad \frac{g_{N\phi}}{g_{N\omega}} = -\frac{\sqrt{3} - 2(4\alpha_V - 1)z}{\sqrt{6} + (4\alpha_V - 1)z}$$

$$\frac{g_{\Lambda\phi}}{g_{N\omega}} = -\frac{\sqrt{3} + 2\sqrt{2}(1-\alpha_V)z}{\sqrt{6} + (4\alpha_V - 1)z}, \qquad \frac{g_{\Sigma\phi}}{g_{N\omega}} = -\frac{\sqrt{3} - 2\sqrt{2}(1-\alpha_V)z}{\sqrt{6} + (4\alpha_V - 1)z}$$