Neutron stars with Bogoliubov quark-meson coupling model

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A quark-meson coupling model based on the quark model proposed by Bogoliubov
for the description of the quark dynamics is developed and applied to the description
of neutron stars. Starting from a su(3) symmetry approach, it is shown that this
symmetry has to be broken in order to satisfy the constraints set by the hypernuclei
and by neutron stars. The model is able to describe observations such as two solar
mass stars or the radius of canonical neutron stars within the uncertainties presently
accepted. If the optical potentials for Λ and Ξ hyperons in symmetric nuclear matter
at saturation obtained from laboratory measurements of hypernuclei properties are
imposed the model predicts no strangeness inside neutron stars.
I. INTRODUCTION

The study of nuclear matter properties has received, in the recent few decades, much attention. Such investigations are particularly important in connection with nuclear-astrophysics. The recent detection of the gravitational waves GW170817 and the follow-up of the electromagnetic counterpart from a neutron star merger [1–3], together with the simultaneous measurement of the radius and mass of the pulsar PSR J0030-0451 by NICER [4, 5] are very important observations to constrain the equation of state (EoS) of dense matter. Besides, the two solar mass pulsars PSR J1614-2230 [6, 7], PSR J0348+0432 [8] and MSP J0740+6620 [9] are also setting important constraints on the nuclear matter EoS at high densities. In particular, these masses put some difficulties on the possible existence of non-nucleonic degrees of freedom, such as hyperons or quark matter, in the inner core of the NS. In [6], it was even suggested that PSR J1614-2230 would rule out the appearance of these degrees of freedom inside pulsars. Since then many works have shown that the present existing constraints on the high density EoS are sufficiently weak to still allow for the onset of hyperons, quarks or other non-nucleonic degrees of freedom inside two solar mass neutron stars [10–16].

In relativistic mean field (RMF) models [17–20], the nucleon-nucleon interaction is described in terms of the coupling of nucleons, assumed to be point particles, with isoscalar scalar mesons, isoscalar vector mesons, and isovector vector mesons. In order to describe adequately nuclear matter properties RMF models include either self- and cross-interactions [18, 19] among these mesons or density dependent couplings [20].

There have been attempts, based on the MIT bag model [21], and on the Nambu-Jona-Lasinio (NJL) model [22], to take into account the quark structure of the nucleon, in order to incorporate the meson couplings at a more basic level. Along these lines, the nuclear equation of state (EoS) has been obtained and the properties of nuclear matter have been determined by Guichon, Saito and Thomas [21, 23, 24], and by others [25–28], in the framework of quark-meson coupling (QMC) models. Still within the same model, in [29, 30] the authors have studied the effect of strong magnetic fields on kaon condensation and hyperonic matter, respectively.

Recently, nuclear matter has also been investigated in the context of a modified QMC model based on the replacement of the nucleon bag by an independent quark potential [31–33]. Motivated by the idea of the string tension, Bogoliubov proposed an independent quark model for the description of the quark dynamics [34]. The phenomenological description of hadronic matter in the spirit of the QMC approach, combined with Bogoliubov’s interesting quark model,
has been considered in [35], for non-strange matter, and in [36], for strange matter. We will refer to the model considered in [35, 36] as the Bogoliubov-QMC model.

In the present study, we consider a generalization of the model proposed in [36], where the couplings of the quarks $s$ to vector bosons have not been explicitly considered. Instead, in [36] it is postulated that the couplings of hyperons to the vector mesons are well constrained by the phenomenological hyperon potentials in nuclear matter. Here, the consequences of considering the coupling of the quarks $u, d, s$ to appropriate vector bosons are explicitly investigated. We discuss under which conditions it is possible to describe two solar mass stars with a non zero strangeness content and determine their chemical content.

In section II we briefly present the model, in section III the description of hadronic matter with strangeness is introduced and the $\beta$-equilibrium equation of state is built. In the section IV, we obtain the structure and properties of neutron stars described by the present models and discuss the results. Finally some concluding remarks are drawn in the last section.

II. THE MODEL

We consider the Hamiltonian

$$h_D = -i\alpha \cdot \nabla + \beta (\kappa |\mathbf{r}| + m - g_\sigma^2 \sigma) .$$  \hspace{1cm} (1)

Here, $m$ is the current quark mass, $\beta$ and the components $\alpha_x, \alpha_y, \alpha_z$ of $\alpha$ are Dirac matrices, $\sigma$ denotes the external scalar field, $g_\sigma^2$ denotes the coupling of the quark to the $\sigma$ field and $\kappa$ denotes the string tension,

$$\beta = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix}, \quad \alpha_x = \begin{bmatrix} 0 & \sigma_x \\ \sigma_x & 0 \end{bmatrix}, \quad \alpha_y = \begin{bmatrix} 0 & \sigma_y \\ \sigma_y & 0 \end{bmatrix}, \quad \alpha_z = \begin{bmatrix} 0 & \sigma_z \\ \sigma_z & 0 \end{bmatrix},$$

where $\sigma_x, \sigma_y, \sigma_z$ are the Pauli matrices. The current quark mass $m$ is taken to be $m = 0$ for $u, d$ quarks because their constituent mass is assumed to be determined exclusively by the value of $\kappa$. The eigenvalues of $h_D$ are obtained by a scale transformation from the eigenvalues of

$$h_{D_0} = -i\alpha \cdot \nabla + \beta (|\mathbf{r}| - a) .$$

We need the lowest positive eigenvalue of $h_{D_0}$. We cannot apply the variational principle to $h_{D_0}$, because its eigenvalues are not bounded from below, but we can apply the variational principle to the square of the Hamiltonian,

$$h_{D_0}^2 = -\nabla^2 + (|\mathbf{r}| - a)^2 + i\beta \alpha \cdot \frac{\mathbf{r}}{|\mathbf{r}|} .$$  \hspace{1cm} (2)
We wish to determine variationally the lowest positive eigenvalue of $h_{D_0}$ versus $a$. The variational ansatz should take into account the Dirac structure of the quark wave-function, so that we consider the following ansatz,

$$\Psi_{b,\lambda} = \chi \frac{e^{-(|r|-a-b)^2/2}}{i\lambda (\sigma \cdot r) \chi},$$

where $b, \lambda$ are variational parameters, and $\chi$ is a 2-spinor. Minimizing the expectation value of $h_{D_0}^2$ for $\Psi_{b,\lambda}$, the following expression for the quark mass is found,

$$m_{\lambda_0}^2(\kappa, a) = \min_{\lambda, b} \frac{\langle \psi_{b,\lambda} | h_{D_0}^2 | \psi_{b,\lambda} \rangle}{\langle \psi_{b,\lambda} | \psi_{b,\lambda} \rangle} = \min_{\lambda, b} \frac{K_0 + V_0 + V_{01} \lambda + (K_1 + V_1) \lambda^2}{N_0 + N_1 \lambda^2},$$

where $N_0, V_0, K_0, N_1, V_1$, and $K_1$ are all given in [35].

Minimization of Eq. (4) with respect to $\lambda$ is readily performed, so that

$$m_{\lambda_0}^2(\kappa, a) = \frac{1}{2} \min_b \left( \frac{K_0 + V_0 + K_1 + V_1}{N_0} - \sqrt{\left( \frac{K_0 + V_0}{N_0} - \frac{K_1 + V_1}{N_1} \right)^2 + \left( \frac{V_{01}}{\sqrt{N_0 N_1}} \right)^2} \right).$$

Minimization of the r.h.s. of Eq. (5) with respect to $b$ may be easily implemented. We have found that in the interval $-1.25 < a < 2.4$, that covers the range of densities we will consider, we may express the groundstate energy, $m(\kappa, a)$, of $h_{D_0}$, with sufficient accuracy, as

$$m(\kappa, a) = 2.64123 - 2.35426a + 0.825225a^2 - 0.072244a^3 - 0.0314736a^4 + 0.00155171a^5 + 0.00257144a^6.$$

Taking $a = g^2_0 \sigma / \sqrt{\kappa}$ for quarks $u, d$, we get, in the vacuum, the constituent mass of these quarks equal to 313 MeV, with $a = 0$ and $\kappa = 37106.931784$ MeV$^2$. For the quark $s$, $a = a_s = -1.2455 + g^2_0 \sigma / \sqrt{\kappa}$ reproduces the vacuum constituent mass 504 MeV of this quark. Consequently, the mass $M_B^*$ of the baryon $B$ is given as follows

$$M_N^* = M_P^* = 3m(\kappa, a), M_L^* = 2m(\kappa, a) + m(\kappa, a_s), M_S^* = m(\kappa, a) + 2m(\kappa, a_s).$$

As we will discuss in the following, the $\Sigma$-hyperons will not be considered, because experimental data seem to indicate that the potential of the $\Sigma$-hyperon in nuclear matter is quite repulsive [37], so that their appearance is disfavored.

### III. HADRONIC MATTER

In order to describe hadronic matter, we introduce the vector-isoscalar $\omega$ meson, the vector-isovector $b_3$ meson and use nuclear matter properties to fix the couplings of these mesons to nucleons.
In the present model, the field $\omega$ is replaced by a vector field of the $\eta$ type, in the spirit of the reference [38], with structure $(\bar{u}u + \bar{d}d + (1 + \delta) \bar{s}s)/\sqrt{2 + (1 + \delta)^2}$, where $1 + \delta > 0$, so that the coupling of the $\omega$-meson to the quark $s$ is equal to the coupling to the quarks $u, \, d$ multiplied by $1 + \delta$. The parameter $\delta$ will be fixed by the potential $U_\Lambda$ of the $\Lambda$-hyperon in symmetric nuclear matter at saturation.

In this framework, the energy density is given by

$$ E = \frac{\gamma}{(2\pi)^3} \left( \sum_{B,(B\neq\Sigma)} \int^{k_F_B} k^3 \sqrt{k^2 + M^*_B} + \sum_l \int^{k_F_l} k^3 \sqrt{k^2 + M_l^2} \right) + \frac{1}{2} m^2 \sigma^2 + \frac{1}{2} m^2 \omega^2 + \frac{1}{2} m^2 b^2, $$

and the thermodynamical potential is given by

$$ \Phi = \frac{\gamma}{2\pi^2} \left( \sum_{B,(B\neq\Sigma)} \int^{k_F_B} k^2 dk \left( \sqrt{k^2 + M^*_B} - (\mu - q_B \lambda) \right) + \int^{k_F_l} k^2 dk \left( \sqrt{k^2 + M_l^2} - \lambda \right) \right) + \frac{1}{2} m^2 \sigma^2 + \frac{1}{2} m^2 \omega^2 + \frac{1}{2} m^2 b^2, $$

where the Lagrange multiplier $\mu$ controls the baryon density and $\lambda$ the electrical charge. The sources of the fields $\omega$ and $b_3$ respectively $\rho_0$, and $\rho_3$ are given by

$$ \rho_0 = \frac{\gamma}{(2\pi)^3} \sum_{B,(B\neq\Sigma)} \zeta_B \int^{k_F_B} d^3k, \quad \rho_3 = \frac{\gamma}{(2\pi)^3} \sum_{B,(B\neq\Sigma)} \eta_B \int^{k_F_B} d^3k, $$

with

$$ \zeta_P = \zeta_N = 1, \quad \zeta_\Lambda = 1 + \delta, \quad \zeta_{\Xi_0} = \zeta_{\Xi_-} = 1 + 2\delta, $$

$$ \eta_P = 1, \quad \eta_N = -1, \quad \eta_\Lambda = 0, \quad \eta_{\Xi_0} = 1, \quad \eta_{\Xi_-} = -1. $$

The relation between the fields and the respective sources is given by

$$ \omega = \frac{3g^2_\omega \rho_0}{m^2_\omega}, \quad b_3 = \frac{g^2_{b_3} \rho_3}{m^2_{b_3}}. $$

We start by fixing the free parameter $\kappa$ of the Bogoliubov model. This is obtained by fitting the nucleon mass $M = 939$ MeV. Next, the desired values of the neutron effective mass $M^*/M = 0.773$, nuclear matter binding energy $E_B = \epsilon/\rho_B - M_N^* = -15.7\text{MeV}$, the incompressibility $K = 315.0$ MeV, in agreement with the range of values proposed in [39], and the radius of the bag $R_B = 0.1163\text{fm}$ at saturation density, $\rho_B = 0.145\text{fm}^{-3}$, are obtained by
Figure 1. Pressure versus potential comparing neutron, proton, leptonic matter with hyperonic matter for \( \delta = 0.0, 0.05, 0.1, 0.15, 0.2 \) and 0.25 (panel left), and energy density versus baryonic density for the same values of the parameter \( \delta \) (panel right), for \( \beta \)-equilibrium nucleonic and hyperonic matter. All EoS obtained for the Bogoliubov-QMC model.

Setting \( g_d^q = 4.0539996 \) and \( 3g_d^q = g_\omega^q = 9.2474196 \). The coupling constant \( g_{b3}^q = 3.9532889 \) is fixed in order to have the symmetry energy coefficient \( a_4 = 29 \text{MeV} \) and the symmetry energy slope \( L = 79.45 \text{MeV} \), at saturation density. The value we consider for \( L \) is well inside the range of values obtained in [40] from a huge number of experimental data and astrophysical observations, \( L = 58.7 \pm 28.1 \text{MeV} \). We have chosen a slightly low saturation density in order that the model produces reasonable values of incompressibility \( K \).

There is an appreciable mass difference between the hyperons \( \Lambda \) and \( \Sigma \), which, according to [41–43] is due to an hyperfine splitting. Moreover, it should be kept in mind that the \( SU(2) \) symmetry is a very important one. The hyperon \( \Lambda \) is an isosinglet; the nucleon and the \( \Xi \) are isodoublets; the \( \Sigma \) is an isotriplet. Besides, it is known that the \( \Sigma \)-nucleus potential in symmetric nuclear matter seems to be repulsive [37, 44]. Our bag model does not take into account the mechanism responsible for the above mentioned hyperfine splitting, the \( \Sigma \) and \( \Lambda \) hyperons are degenerate, and besides also leads to an attractive optical potential for the \( \Sigma \). We overcome this problem by omitting the \( \Sigma \) in sums over \( B \), as explicitly indicated in (9), and in analogous sums in the sequel. We are only performing sums over baryons which are either isosinglets or isodoublets. The omission of the \( \Sigma \)-hyperon is in accordance with the general result obtained when a repulsive \( \Sigma \)-potential in symmetric matter at saturation density of the order of 30 MeV is considered [11, 12, 16]: \( \Sigma \)-hyperons are not present inside neutron stars.
Figure 2. Baryonic and leptonic particle fractions as a function of the baryonic density, for several values of the parameter $\delta$. For $\delta = 0.25$ the onset of hyperons is shifted to densities above $1.2 \text{ fm}^{-3}$. The central baryonic density lies between 0.9 and 1.1 fm$^{-3}$ depending on the hyperonic content.

Table I. Properties of the stable neutron star with maximum mass, for several values of $\delta$, $M_{\text{max}}$, $M_{\text{max}}^b$, $R$, $E_0$, $\rho^c$, $R_{1.4}$, $R_{1.6}$, $U_\Lambda(\rho_0)$ and $U_\Xi(\rho_0)$ are respectively, the gravitational and baryonic masses, the star radius, the central energy density, the central baryonic density, the radius of neutrons star calculated for $1.4M_\odot$ and $1.6M_\odot$, and the optical potentials for a $\Lambda$ and $\Xi$-hyperon in symmetric nuclear matter at saturation.

| $\delta$ | $M_{\text{max}}$ | $M_{\text{max}}^b$ | $R$ | $E_0$ | $\rho^c = \rho^c/\rho_0$ | $R_{1.4}$ | $R_{1.6}$ | $U_\Lambda(\rho_0)$ | $U_\Xi(\rho_0)$ |
|---------|-----------------|-----------------|-----|-------|-------------------|---------|---------|----------------|----------------|
| 0.0     | 1.97            | 2.28            | 10.91 | 7.25  | 7.674             | 13.731  | 13.492  | -75.34         | -93.99         |
| 0.02    | 2.02            | 2.34            | 11.16 | 6.85  | 7.293             | 13.740  | 13.624  | -72.23         | -87.77         |
| 0.05    | 2.08            | 2.43            | 11.42 | 6.43  | 6.882             | 13.752  | 13.680  | -67.57         | -78.45         |
| 0.1     | 2.16            | 2.53            | 11.73 | 5.97  | 6.429             | 13.750  | 13.693  | -59.80         | -62.91         |
| 0.15    | 2.20            | 2.58            | 11.83 | 5.84  | 6.285             | 13.746  | 13.698  | -52.03         | -47.37         |
| 0.2     | 2.21            | 2.60            | 11.84 | 5.81  | 6.256             | 13.748  | 13.697  | -44.26         | -31.83         |
| 0.25    | 2.21            | 2.60            | 11.84 | 5.82  | 6.255             | 13.746  | 13.696  | -36.49         | -16.29         |
| npemu   | 2.21            | 2.60            | 11.84 | 5.84  | 6.272             | 13.746  | 13.696  | -36.49         | -16.29         |
Figure 3. Mass-radius curves obtained from the integration of the TOV equations, for different values of the $\delta$ parameter. The curves stop at the maximum mass configuration. The family of stars for nucleonic stars constituted by $npe\mu$ matter is also represented.

Minimization of $\Phi$ with respect to $k_{FB}$ leads to

$$\sqrt{k_{FB}^2 + M_B^2 + 3g_\omega^q b_3 \eta_B} = \mu - q_B \lambda.$$  \hspace{1cm} (12)

The quantity $\mu - q_B \lambda$ is usually referred to as the chemical potential of baryon $B$. Minimization of $\Phi$ with respect to $k_{Fe}$ leads to

$$\sqrt{k_{Fe}^2 + M_e^2} = \lambda,$$  \hspace{1cm} (13)

so the Lagrange multiplier $\lambda$ is usually called the electron Fermi energy.

Explicitly, for $N$, $\Lambda$, $\Xi$, (12) reduces to

$$\sqrt{k_{FN}^2 + M_N^2 + 3g_\omega^q b_3 \eta_N} = \mu - q_N \lambda,$$
$$\sqrt{k_{F\Lambda}^2 + M_\Lambda^2 + 3g_\omega^q (1 + \delta) \omega} = \mu,$$
$$\sqrt{k_{F\Xi}^2 + M_\Xi^2 + 3g_\omega^q (1 + 2\delta) \omega + g_\omega^{q_b} b_3 \eta_\Xi} = \mu - q_\Xi \lambda.$$

Then, according to the prescription of (45), we have

$$U_\Lambda := M_\Lambda^* - M_\Lambda + 3g_\omega^q (1 + \delta) \omega,$$
$$U_\Xi := M_\Xi^* - M_\Xi + 3g_\omega^q (1 + 2\delta) \omega,$$
and it is possible to fix the coupling to the quark s in such a way that a reasonable $U_\Lambda$, is obtained. We find that a small change of $\delta$ leads to big changes of $U_\Lambda$ and $U_\Xi$. However, the EoS is almost insensitive to the value of $\delta$ for a wide range of values of $U_\Lambda$ around the proper one. This model predicts a competition between negatively charged hyperons and leptons. This is natural in view of Bodmer-Witten’s Conjecture [46, 47], according to which the groundstate of baryonic matter at high densities should involve only quarks $u, d, s$, without leptons.

In order to study the structure of neutron stars described by the present model we have integrated the Tolman-Oppenheimer-Volkov equations for spherical stars in equilibrium [48, 49]. The complete EoS was obtained matching the Baym-Pethcik-Sutherland EoS for the outer crust [50], and the inner crust obtained within a Thomas Fermi description of the non-homogeneous matter for the NL3$\omega\rho$ model with the symmetry energy slope at saturation equal to 77 MeV [51], to the core EoS.

For $\delta = 0$, we find that the EoS is too soft. However, a mass of 1.92 solar masses and a radius of about 11 km are reached in the present model with $K = 315$ MeV. For $\delta \geq 0.2$, the EoS and the curve mass vs. radius are almost insensitive to the value of $\delta$. The onset of hyperons occurs at a density above $\sim 0.6 \text{ fm}^{-3}$ and the hyperon fraction is too small. Let us point out that we obtain reasonable values for the hyperon-potentials in symmetric nuclear matter for $\delta \sim 0.25$. With this value of $\delta$ no hyperons will appear inside neutron stars. A similar conclusion was obtained by [52] within a microscopic approach that includes three body contributions of the form $NNY$. Under these results, two solar mass stars will not contain hyperons because they will set in at densities of the order of the neutron star central density or above.

The canonical star with a mass 1.4 $M_\odot$ has a mass of the order of 13.7 km, well within the values obtained by NICER [4, 5] and other observations [53], and within or just slightly above the prediction obtained from terrestrial data [54], or the gravitational wave GW170817 [1, 2] detected by LIGO/Virgo from a neutron neutron star merger [55, 56, 58]. We have calculated the tidal deformability of a canonical star with a mass 1.4$M_\odot$ according to [59]. The result obtained was $\Lambda_{1.4} = 936 - 954$ depending on the hyperon content, well above the prediction of $2 \times 70 < \Lambda_{1.4} < 580$, which however was determined from a set of models that do not necessary describe two solar-mass stars. These high values of $\Lambda_{1.4}$ may indicate that the symmetry energy is too stiff as discussed in [56, 57], and the inclusion of a non-linear $\omega - \rho$ term will soften the symmetry energy at high densities, and decrease the value of $\Lambda_{1.4}$.

Within the present model we are able to describe NS as massive as the pulsar MSP J0740+6620 [4], in particular, if we constraint the optical potential of the $\Lambda$-hyperon in sym-
metric matter to experimental values. Only the hyperon fraction of baryonic matter and the value of the optical potential are sensitive to the precise value of $\delta$, for $\delta \geq 0.2$.

### IV. CONCLUSIONS

In the present study we have developed a QMC model based in the Bogoliubov quark model. The nucleons interact via the exchange of a scalar-isoscalar meson, a vector-isoscalar meson and a vector-isovector meson. The nucleon mass is derived from the energy of the bag which includes $u$, $d$ and $s$ quarks. The parameters introduced at this level are chosen so that the vacuum constituent quarks masses are reproduced. Hadronic matter is described by introducing a vector-isoscalar $\omega$-meson, which also includes a $\bar{s}s$ content, and a vector-isovector $b_3$-meson. In order to satisfy constraints imposed by neutron stars and hypernuclei it is shown that the coupling of the $\omega$-meson to the $s$-quark must be more repulsive than its coupling to the $u$, and $d$-quarks, and a parameter that takes this aspect into account has to be introduced, so that $\text{su}(3)$ symmetry is broken.

The couplings of the mesons to the nucleons were fixed so that nuclear matter properties, binding energy, saturation density, incompressibility, symmetry energy and its slope at saturation, are adequately described. Once these parameters are fixed, only the parameter that defines how repulsive is the coupling of the $\omega$-meson to hyperons, remains to be fixed. Taking the optical potential of the $\Lambda$-hyperon of the order of $-30$ MeV as discussed in [37, 60, 61], no hyperons will be present inside a two-solar mass. A similar conclusion has been drawn in [52] where, within an auxiliary field diffusion Monte Carlo algorithm, it was shown that the three-body hyperon-nucleon interaction has an important role in softening the EoS at large densities. Using experimental separation energies of medium-light hypernuclei to constraint the $\Lambda NN$ force, they have shown that the onset of hyperons will occur above $0.56 \text{ fm}^{-3}$, and concluded that with the presently available experimental energies of $\Lambda$-hypernuclei it is not possible to draw a conclusive statement concerning the presence of hyperons inside neutron stars.

The present model predicts for the canonical neutron star a radius that is compatible with observations and predictions from the analysis of the GW170817 detection. The tidal deformability, is however, too large, and this may indicate that the symmetry energy is too stiff. A softer symmetry energy may be generated with the inclusion of a non-linear $\omega - \rho$ term in
the model [62].
12

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