We generalize the Bogoliubov quark-meson coupling model to also include hyperons. The hyperon-σ-meson couplings are fixed by the model and the hyperon-ω-meson couplings are fitted to the hyperon potentials in symmetric nuclear matter. The present model predicts neutron stars with masses above $2M_\odot$ and the radius of a $1.4M_\odot$ star equal to 13.83 km.
I. INTRODUCTION

The properties of nuclear matter has been an area of interest for the past few decades. Such studies are quite important in nuclear physics in the context of nucleon-nucleon \((NN)\) interaction, structure and properties of finite nuclei, dynamics of heavy ion collisions, nuclear-astrophysics and also particle physics. The relativistic mean field (RMF) models \([1–4]\) represent the \(NN\) interactions through the coupling of nucleons with isoscalar scalar mesons, isoscalar vector mesons, isovector vector mesons, and the photon quanta besides the self- and cross-interactions \([2, 3]\) among these mesons, or density dependent couplings \([4]\).

In the above RMF models, the nucleons are treated as structureless point objects. However, incorporation of structure of nucleon with meson couplings at the basic quark level in the study of saturation properties of nuclear matter can provide new insight. Having this in mind, there have been several attempts based on the MIT bag model \([5]\) and on the Nambu-Jona-Lasinio (NJL) model \([6]\) to address the nucleon structure. Using such quark-meson coupling (QMC) models, the nuclear equation of state (EOS) has also been constructed and properties of nuclear matter have been studied in great detail in a series of works by Guichon, Saito and Thomas \([5, 7, 8]\) and by others \([9–12]\). Recently the modified quark-meson coupling model which is based on confining relativistic independent quark potential model rather than a bag to describe the baryon structure in vacuum, has been extensively applied for the study of the bulk properties of both symmetric as well as asymmetric nuclear matter \([13–15]\).

The aim of the present work is to obtain a phenomenological description of hadronic matter including hyperonic degrees of freedom, in the spirit of the QMC approach, combined with the Bogoliubov model \([16]\) for the description of the quark dynamics in the nucleon \([17]\). We will refer to the present model the Bogoliubov-QMC model. In \([17]\), symmetric and asymmetric nuclear matter at saturation density have been successfully described. In the present study we will generalize the model in order to include hyperons and will study the structure of neutron stars within this model.

II. EQUATION OF STATE

The independent quark model of the nucleon proposed by Bogoliubov \([16]\) is described by the Hamiltonian

\[
h_D = -i\mathbf{\alpha} \cdot \nabla + \beta (\kappa |\mathbf{r}| + m - g_s \sigma),
\]  

(1)
where \( m \) 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, \( g^q_\sigma \) denotes the coupling of the quark to the \( \sigma \) field and \( \kappa \) denotes the string tension. The constituent quark mass is obtained by solving the Dirac equation,

\[
[\alpha \cdot \mathbf{p} + \beta(\kappa|\mathbf{r}| + m - g^q_\sigma \sigma)] \psi_q = \varepsilon_q \psi_q. \tag{2}
\]

The current quark \( m \) is taken to be \( m = 0 \) for \( u,d \) quarks because their constituent mass is assumed to be determined exclusively by the value of \( \kappa \). For the \( s \)-quark the value \( m = 232.633 \text{ MeV} \) has been chosen in order to reproduce the \( \Lambda \)-hyperon mass 1130 MeV in the vacuum, with the same value of \( \kappa \) which has been considered for quarks \( u,d \).

The eigenvalues of \( h_D \) are obtained by a scale transformation from the eigenvalues of

\[
h_{D0}^2 = -\nabla^2 + (|\mathbf{r}| - a)^2 + i\beta \alpha \cdot \frac{\mathbf{r}}{|\mathbf{r}|}, \tag{3}
\]

and looking for the respective eigenvalues versus \( a \). For \( a = 0 \) the groundstate eigenvalue of \( h_{D0}^2 \) reads 2.6402 in units of \( \kappa \) [17]. \( \kappa \) takes the value

\[
\kappa = \frac{313^2}{2.6402} \text{ MeV}^2 = 37106.9317 \text{ MeV}^2,
\]

so as to reproduce the constituent mass 313 MeV of quarks \( u,d \) in vacuum. For completeness sake, we describe in the Appendix the procedure followed in [17] to determine variationally the groundstate wave function of \( h_{D0}^2 \).

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 ground state energy, \( m(\kappa, a) \), of \( h_{D0} \), with sufficient accuracy, as

\[
\frac{(m(\kappa, a))^2}{\kappa} = 2.64022 - 2.3644a + 0.76534a^2 - 0.0468815a^3 - 0.0131333a^4 - 0.00323908a^5 + 0.00117542a^6. \tag{4}
\]

We take \( a = g^q_\sigma \sigma/\sqrt{\kappa} \) for quarks \( u,d \) because, in vacuum, the constituent mass 313 MeV of these quarks is described with \( a = 0 \) and \( \kappa = 37106.9317 \text{ MeV}^2 \). For the quark \( s \), \( a = a_s = -1.2455 + g^q_\sigma \sigma/\sqrt{\kappa} \) reproduces the vacuum constituent mass 504 MeV of this quark.

Thus, the constituent mass of quarks \( u,d \) is

\[
m_u = m_d = \sqrt{\kappa (2.64022 - 2.3644a + 0.76534a^2 - 0.0468815a^3 - 0.0131333a^4 - 0.00323908a^5 + 0.00117542a^6)^{1/2},}
\]
where \( a = a_u = a_d = g_\sigma^q \sigma/\sqrt{\kappa} \), and the constituent mass of quarks \( s \) is

\[
m_s = \sqrt{\kappa} \left( 2.64022 - 2.3644a + 0.76534a^2 - 0.0468815a^3 - 0.0131333a^4 - 0.00323908a^5 + 0.00117542a^6 \right)^{1/2},
\]

where \( a = a_s = -1.2455 + g_\sigma^q \sigma/\sqrt{\kappa} \).

The mass \( M_B^* \) of the baryon \( B \) is

\[
M_B^* = M_P^* = 3m_u, \quad M_\Sigma^* = 2m_u + m_s, \quad M_\Xi^* = m_u + 2m_s.
\]

According to Guichon’s QMC model \([5, 8]\), the energy density of hadronic matter is given by

\[
\mathcal{E} = \frac{\gamma}{(2\pi)^3} \sum_B \int d^3k \left( \sqrt{k^2 + M_B^*} + 3g_\omega^q \omega + g_\rho^q \eta_B b_3 \right) + \frac{1}{2}m_\sigma^2 \sigma^2 - \frac{1}{2}m_\omega^2 \omega^2 - \frac{1}{2}m_\rho^2 b_3^2
\]

where \( \gamma = 2 \) is the spin multiplicity and \( g_\omega^q, g_\rho^q \) are quark-meson coupling constants. The baryon density, which is the source of the field \( \omega \), and the isospin density, the source of the field \( b_3 \), are given, respectively, by

\[
\rho_B = \frac{\gamma}{2\pi^2} \sum_B \int k_F^B k^2 dk, \quad \rho_3 = \frac{\gamma}{2\pi^2} \sum_B \eta_B \int k_F^B k^2 dk,
\]

with \( \eta_P = 1, \eta_N = -1, \eta_\Lambda = \eta_\Xi = 0, \eta_\Sigma^+ = 2, \eta_\Sigma^- = -2, \eta_\Xi^+ = 1, \eta_\Xi^- = -1 \).

The relation between the fields \( \omega, b_3 \) and the respective sources is obtained minimizing \( \mathcal{E} \) in \((5)\) with respect to \( \omega, b_3 \). We find

\[
\omega = \frac{3g_\omega^q \rho_B}{m_\omega^2}, \quad b_3 = \frac{g_\rho^q \rho_3}{m_\rho^2}. \tag{7}
\]

In order to describe beta decay equilibrium, the presence of electrons and muons must also be considered, so the energy density becomes

\[
\mathcal{E} = \frac{\gamma}{(2\pi)^3} \left( \sum_B \int d^3k \sqrt{k^2 + M_B^*} + \sum_i \int d^3k \sqrt{k^2 + M_i^*} \right) + \frac{1}{2}m_\sigma^2 \sigma^2 + \frac{1}{2}m_\omega^2 \omega^2 + \frac{1}{2}m_\rho^2 b_3^2, \tag{8}
\]

where \( k_{Fi} \) and \( M_i \) denote, respectively, the lepton Fermi momentum and mass.

The energy density \( \mathcal{E} \) in \((8)\) should be minimized with respect to the baryonic and the lepton Fermi momenta, respectively, \( k_{F_B} \) and \( k_{Fi} \), under constraints for the prescribed baryon number \( \rho_B \), and the charge neutrality condition,

\[
\frac{\gamma}{2\pi^2} \left( \sum_B q_B \int k_{F_B} k^2 dk - \int k_{Fi} k^2 dk \right) = 0.
\]
with $q_B = 1$ for positively charged baryons, $q_B = 0$ for neutral baryons and $q_B = -1$ for negatively charged baryons. The Lagrange multiplier controlling the baryon number is the baryon chemical potential $\mu$ and the Lagrange multiplier controlling the charge, is denoted by $\lambda$. The Lagrange function is readily obtained. It is the thermodynamical potential and is given by

$$\Phi = \frac{\gamma}{2\pi^2} \left( \sum_B \int^{k_{fB}} k^2 dk \left( \sqrt{k^2 + M_B^2} - (\mu - q_B \lambda) \right) + \int^{k_{fL}} k^2 dk \left( \sqrt{k^2 + M_l^2} - \lambda \right) \right) + \frac{1}{2} m^2 \sigma^2 + \frac{1}{2} m^2 \omega^2 + \frac{1}{2} m^2 \rho^2_{b3},$$

(9)

where the fields $\omega, b_3$ are given in (7). Minimization of $\Phi$ with respect to $k_{fB}$ leads to

$$\sqrt{k_{fB}^2 + M_B^2} + 3g^2_\omega \omega + g^2_\rho b_3 \eta_B = \mu - q_B \lambda.$$  

(10)

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

$$\sqrt{k_{fL}^2 + M_l^2} = \lambda,$$

(11)

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

To summarize, in order to describe neutral matter in $\beta$ equilibrium, we have to minimize the energy density (8) with respect to the Fermi momenta $k_{fB}, k_{fL}$ and $\sigma$, for fixed baryon density and vanishing charge density. Equivalently, the Fermi momenta $k_{fB}, k_{fL}$ are obtained by solving the set of simultaneous equations (10), (11), followed by minimization with respect to $\sigma$. In the end, it must be ensured that $\lambda$ is such that the charge density vanishes.

### III. RESULT AND DISCUSSIONS

We start by fixing the free parameter $\kappa$ for the Bogoliubov model. This is obtained by fitting the nucleon mass $M = 939$ MeV. The desired values of nuclear matter binding energy $E_B = \varepsilon/\rho_B - M_N = -15.7$ MeV at saturation density, $\rho_B = 0.15$ fm$^{-3}$ are obtained by setting $g^4_\omega = 3.982$ and $3g^4_\omega = g_{\omega N} = 9.3001$. The coupling $g^4_\rho = g_{\rho N} = 8.601$ is fixed so that $E_{sym} = 32.5$ MeV at saturation density. In the Bogoliubov-QMC, the couplings of the hyperons to the sigma meson do not need to be fixed because the effective masses of the baryons are determined through the three quark bound. Only $x_{\omega B}$ and $x_{\rho B}$ have to be fixed. We obtain $x_{\omega B}$ from the hyperon potentials in nuclear matter, $U_B = -(M_B^* - M_B) + x_{\omega B} g_{\omega N} \omega_0$ for $B = \Lambda, \Sigma$, and $\Xi$ to be $-28, 30,$ and $-18$ MeV, respectively. We find that $x_{\omega \Lambda} = 0.73$, $x_{\omega \Sigma} = 1.1$ and
$x_{\omega\Xi} = 0.52$, respectively for the coupling of the $\omega$-meson to the $\Lambda$, the $\Sigma^{\pm,0}$ and the $\Xi^{-,0}$. It is worth mentioning here that the binding of $\Lambda$ to symmetric nuclear matter is quite well settled experimentally, although it can vary within $\sim -31 \pm 3$ MeV [18], while the binding values of $\Sigma^{-}$ and $\Xi^{-}$ still have large uncertainties. For the $\Sigma$-hyperon it is supposed that the potential is repulsive because no $\Sigma$-hypernucleus has been measured. The value +30 MeV that has been considered is only indicative and it should be taken with care. In fact, it gives origin to a value of $x_{\omega\Sigma}$ just above 1 that may be considered too large. Taking a smaller value of $U_{\Sigma}$ would decrease $x_{\omega\Sigma}$ but the overall results would not change. The presently existing experimental results for the $\Xi$-hypernuclei seem to indicate that the hyperon potential at 2/3 to 1 $\rho_0$, where $\rho_0$ is the saturation density, is approximately 14 MeV [19]. We have considered $U_{\Xi}(\rho_0) = -18$ MeV, a value frequently taken in the literature. For the $\rho$-meson-hyperon coupling we consider $x_{\rho B} = 1$, and the relative strength for each species is defined by the isospin component, in particular it does not couple to the hyperons $\Lambda$, $\Sigma^{0}$ and $\Xi^{0}$.

![Figure 1. EoS for pure neutron matter and for nucleonic matter and hyperonic matter in $\beta$-equilibrium with electrons and muons.](image)

In figure (1), we show the equation of state for the pure neutron matter, neutron-proton in $\beta$-equilibrium and the hyperon matter in $\beta$-beta equilibrium. As expected, the neutron EoS is the hardest one and the hyperonic EoS the softest one.

In figure (2) we have plotted the baryonic and the leptonic particle fractions. As in other models, that take similar potentials for the hyperons in symmetric matter, the $\Lambda$-hyperon is the first hyperon to set in and the $\Xi^{-}$ the second one [20]. In the present model $\Xi^{0}$ is the third hyperon to set in but this is not always the case as shown in [21]. At high density, the hyperonic
Figure 2. Baryonic and leptonic particle fractions as a function of the baryonic density. At high densities, the numbers of leptons present are small.

content is influenced if the mesons with hidden strangeness as $\sigma^*$ and $\phi$ are also included in the model [18, 22]. Due to the large uncertainties with respect to fixing their couplings, as information on double hyperon nuclei is residual, in the present study we do not consider them.

Figure 3. Neutron star mass versus the radius for neutron matter EoS and the $\beta$-equilibrium nucleonic and hyperonic EoS, all three EoS obtained for the Bogoliubov-QMC model.

We next proceed to calculate the properties of neutron stars using the Boboliubov-QMC model. The equation of state enters as input to the TOV equation which generates the macroscopic stellar quantities, the mass and the radius. In Table I the properties of the maximum
Table I. Neutron star properties obtained from the integration of the TOV equations, maximum gravitational and baryonic masses and respective radius and central energy density, radius of a 1.4\(M_\odot\) star and

|                     | \(M(M_\odot)\) | \(M_b(M_\odot)\) | R (km) | \(\varepsilon_c(\text{fm}^4)\) | \(R_{1.4}\) (km) |
|---------------------|----------------|-----------------|--------|-----------------|-----------------|
| n matter            | 2.39           | 2.83            | 12.63  | 5.08            | 14.54           |
| np+e+\(\mu\) matter| 2.24           | 2.63            | 11.95  | 5.70            | 13.86           |
| hyperon+e+\(\mu\) matter | 2.03       | 2.35            | 12.67  | 4.81            | 13.86           |

mass star are given together with the radius of the canonical star with \(M = 1.4M_\odot\). All scenarios describe a \(2M_\odot\) star as imposed by the pulsars PSR J0348+0432 and PSR J1614–2230. Considering the radius of the 1.4 \(M_\odot\) stars, they lie within the observation data compiled in [26] which are still not too restrictive due to large uncertainties. Predictions for the \(R_{1.4}\) were also obtained from the recently detection the gravitational waves GW170817 from the merging of two neutron stars: \(8.7 \leq R_{1.4} \leq 14.1\) km [27] or \(11.82 \leq R_{1.4} \leq 13.72\) km [28]. The predictions from our model are within the range defined in [27] and not far from the upper limit obtained in [28].

### A. Bodmer-Witten conjecture

According to the “strange matter hypothesis” of Bodmer and Witten [29, 30], when the number of quarks is very large, the lowest energy state is such that it has the same number of up, down, and strange quarks. This stability is considered to be a consequence of the Pauli exclusion principle, because, for three types of quarks instead of two, as in normal nuclear matter, more quarks may be placed in the lower energy levels. This hypothesis may be extended to hyperons, rather than quarks. Indeed, according to the Pauli exclusion principle, it is even more advantageous to have six hyperons instead of two nucleons.

In order to discuss the Bodmer-Wigner hypothesis [29, 30], we replace eq. [12] by

\[
\Phi = \frac{\gamma}{(2\pi)^3} \sum_B \int_{k_{FW}}^k d^3k \left( \sqrt{k^2 + M_B^2} - \mu \right) + \frac{1}{2} m^2 \sigma^2 + \frac{1}{2} m^2 \omega^2,
\]

where the common Fermi momentum of all baryons, \(k_{FW}\), is the solution of the following
equation,
\[ \sum_B \sqrt{k_{FW}^2 + M_B^2} + 3g_\omega^2 \omega = \mu. \]
The vector field does not contribute and the source of the \( \omega \) field is given by
\[ \rho = \frac{8\gamma}{(2\pi)^3} \int k_{FW} \, d^3k, \]
where the factor 8 accounts for the flavor degeneracy. The Bodmer-Wigner hypothesis is asymptotically exact in the context of the Bogoliubov independent quark model and is a good approximation to eq. (9) already at the center of the star densities, as Figs. 4 and 5 demonstrate.

Figure 4. (Witten) Energy density vs. \( \rho \). Approximation based on Witten conjecture (red curve); exact result including hyperons and beta equilibrium (black curve).

Fig. 2 shows that for \( \rho = 1 \text{fm}^{-3} \), there are very few leptons. Moreover, some hyperons are more abundant than others, depending on their masses and charges. What is surprising is that, as Figs. 4 and 5 show, the performance of approximation based on the Bodmer-Witten hypothesis, which ignores the difference in mass of the several hyperons, is so good, much better than it might be expected, at first sight. At low density, the flavor \( su(2) \) symmetry prevails, but at high densities the flavor \( su(3) \) symmetry is rather well restored. It may also be noticed that the Bogoliubov bag is spherical and the quarks sit at the surface. As Eq. (3) of [17] shows, the radius of the bag is \( g_\omega^2 \sigma/\kappa \). It may be seen that at the neutron star center, a sphere with the radius of the bag contains about 8 nucleons. In this sense, it may be said that deconfinement is taking place.
IV. CONCLUSIONS

We have investigated a relativistic model, the Bogoliubov-QMC model, of neutral hyperonic matter in beta equilibrium in which the quarks, up, down and strange, are considered fundamental constituents, and hyperons are described as composite particles, in the framework of Bogoliubov’s independent quark model. The quarks interact in the vacuum through a linear interaction, and medium effects are taken into account through the coupling of the quarks to mesons fields. The mesonic fields are obtained through a minimization of the thermodynamical potential. The parameters of the model are chosen so that saturation nuclear matter properties are described. The size of the baryonic bags increases with density, and for a density of about 0.8 fm$^{-3}$ they strongly overlap, suggesting a phase transition to quark matter. Thus, an interesting EoS embodying the hadron-quark phase transition may be regarded to have been obtained. It is found that strangeness softens the EoS and leads to a convenient reduction of the neutron star radius. The structure of neutron stars described within the present framework have been calculated and it was shown that the model predicts masses above 2$M_\odot$ even if hyperons are taken into account. Also the radius of the canonical neutron star mass with a mass equal to 1.4 $M_\odot$ comes within expected values.
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V. APPENDIX

The trial wave function $\Psi_{b,\lambda}$ of $h_{D0}^2$ considered in [17] contains 2 variational parameters, $\lambda$ and $b$. Minimizing the expectation value of $h_{D0}^2$ with respect to $\lambda$ and $b$, the following expression for the quark mass is found,

$$
\frac{m^2(\kappa, a)}{\kappa} = \min_{\lambda, b} \langle \psi_{b,\lambda} | h_{D0}^2 | \psi_{b,\lambda} \rangle = \min_{\lambda, b} \frac{\mathcal{K}_0 + \mathcal{V}_0 + \mathcal{V}_01 \lambda + (\mathcal{K}_1 + \mathcal{V}_1) \lambda^2}{\mathcal{N}_0 + \mathcal{N}_1 \lambda^2}.
$$

(12)

Minimization of eq. (12) w.r.t. $\lambda$ is readily performed, so that

$$
\frac{m^2(\kappa, a)}{\kappa} = \frac{1}{2} \min_{b} \left( \mathcal{K}_0 + \mathcal{V}_0 + \mathcal{K}_1 + \mathcal{V}_1 - \sqrt{\left( \frac{\mathcal{K}_0 + \mathcal{V}_0}{\mathcal{N}_0} - \frac{\mathcal{K}_1 + \mathcal{V}_1}{\mathcal{N}_1} \right)^2 + \left( \frac{\mathcal{V}_01}{\sqrt{\mathcal{N}_0\mathcal{N}_1}} \right)^2} \right).
$$

(13)

The quantities $\mathcal{K}_0, \mathcal{V}_0, \mathcal{N}_0, \mathcal{K}_1, \mathcal{V}_1, \mathcal{N}_1, \mathcal{V}_01$ depend on $b$ and are given in [17]. Minimization of the r.h.s. of eq. (13) with respect to $b$ may be easily implemented. The result of this minimization is well reproduced by (4) in the considered interval.

In order to obtain the EoS, we need the quark mass under the effect of an external scalar field, $m(\kappa, g_\sigma/\sqrt{\kappa})$.

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