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4 July 1996

Physics Letters B 380 (1996) 13–17

PHYSICS LETTERS B

Massive quarks in neutron stars

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Received 8 December 1995; revised manuscript received 17 April 1996
Editor: C. Mahaux

Abstract

We study various neutron star properties using the Color-Dielectric model to describe quark matter. For the baryon sector at low densities we employ the Walecka model. Applying Gibbs criteria to this composite system, we find that, for matter at β-equilibrium, the pure hadronic phase ends at 0.11 fm^{-3} and that the mixed quark and hadronic phase extends to 0.31 fm^{-3}. The resulting equation of state yields a maximum neutron star mass of $1.59 M_{\odot}$. A neutron star with total mass of $1.4 M_{\odot}$ will consist of a crust made of hadronic matter only, a $\sim$ 1 km thick region of mixed phase and a core composed of pure quark matter. Implications for the cooling of neutron stars are discussed.

PACS: 97.60.Jd; 12.39.-x; 24.85.+p
Keywords: Equation of state; Massive quark matter; Neutron stars

The equation of state (EOS) for dense matter is central to calculations of neutron-star properties, such as the mass range, the mass-radius relationship, the crust thickness and the cooling rate, see e.g. Refs. [1,2]. The same EOS is also crucial in calculating the energy released in a supernova explosion.

The typical density range of a neutron star stretches from central densities of the order of 5 to 10 times the nuclear matter saturation density $n_0 = 0.17$ fm^{-3} to very small values at the edge of the star. Clearly, the relevant degrees of freedom will not be the same in the crust, where the density is much smaller than n_0, and in the center of the star where the density is so high that models based solely on interacting nucleons are questionable. Data from neutron stars indicate that the EOS should probably be moderately stiff in order to support maximum neutron star masses in a range from approximately $1.4 M_{\odot}$ to $1.9 M_{\odot}$ [3]. In addition, simulations of supernovae explosions seem to require an EOS which is even softer. A combined analysis of the data coming from binary pulsar systems and from neutron star formation scenarios can be found in Ref. [4], where it is shown that neutron star masses should fall predominantly in the range $1.3 \leq M/M_{\odot} \leq 1.6$.

The aim of this work is to study properties of neutron stars like cooling rate, total mass and radius employing a massive quark model, the so-called Color-Dielectric model (CDM) [5–7]. The CDM is a confinement model which has been used with success to study properties of single nucleons, such as structure functions [8] and form factors [9], or to describe the interaction potential between two nucleons [10], or to investigate quark matter [7,11]. In particular, it is possible, using the same set of parameters, both to describe the single nucleon properties and to obtain meaningful results for the deconfinement phase tran-

PII S0370-2693(96)00479-0

sition [7]. The latter happens at a density of the order of 2–3 times n_0 when symmetric nuclear matter is considered, and at even smaller densities for matter in β-equilibrium, as discussed below in this work.

Another important feature is that effective quark masses in the CDM are always larger than a value of the order of 100 MeV, hence chiral symmetry is broken and the Goldstone bosons are relevant degrees of freedom. This is to be contrasted with models like the MIT bag, where quarks have masses of a few MeV. We therefore expect the CDM to be relevant for computing the cooling rate of neutron stars *via* the URCA mechanism, as suggested by Iwamoto [12].

The Lagrangian [1] of the model is given by:

$$\begin{aligned}\mathcal{L} &= i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi \\ &+\sum_{f=u,d}\frac{g_f}{f_\pi\chi}\bar{\psi}_f\left(\sigma+i\gamma_5\boldsymbol{\tau}\cdot\boldsymbol{\pi}\right)\psi_f+\frac{g_s}{\chi}\bar{\psi}_s\psi_s \\ &+\tfrac{1}{2}\left(\partial_\mu\chi\right)^2-V(\chi) \\ &+\tfrac{1}{2}\left(\partial_\mu\sigma\right)^2+\tfrac{1}{2}\left(\partial_\mu\boldsymbol{\pi}\right)^2-U(\sigma,\boldsymbol{\pi})\ ,\end{aligned} \tag{1}$$

where $U(\sigma,\boldsymbol{\pi})$ is the "mexican-hat" potential, as in Ref. [13]. The lagrangian $\mathcal{L}$ describes a system of interacting u, d and s quarks, pions, sigmas and a scalar-isoscalar chiral singlet field χ whose potential $U(\chi)$ is given by

$$V(\chi)=\tfrac{1}{2}\mathcal{M}^2\chi^2. \tag{2}$$

The coupling constants are given by $g_{u,d}=g(f_\pi\pm\xi_3)$ and $g_s=g(2f_K-f_\pi)$, where $f_\pi=93$ MeV and $f_K=113$ MeV are the pion and the kaon decay constants, respectively, and $\xi_3=f_{K^\pm}-f_{K^0}=-0.75$ MeV. These coupling constants depend only on a single parameter g. The $SU(3)_f$ version of the model has been introduced by Birse and McGovern [14,15].

When considering a single hadron, confinement is obtained *via* the effective quark masses $m_{u,d}=g_{u,d}\bar{\sigma}/(\bar{\chi}f_\pi)$ and $m_s=g_s/\bar{\chi}$, which diverge outside the nucleon. Indeed, the classical fields $\bar{\chi}$ and $\bar{\sigma}$ are solutions of the Euler–Lagrange equations and $\bar{\chi}$ goes asymptotically to zero at large distances.

The model parameters g and $\mathcal{M}$ are fixed so as to reproduce the experimental mass and radius of the nucleon. In order to describe the single nucleon state, a double projection on linear and angular momentum eigenstates has to be performed, see Ref. [13]. We will use the parameters $g=0.023$ GeV and $\mathcal{M}=1.7$ GeV, giving a nucleon isoscalar radius of 0.80 fm (exp.val.=0.79 fm) and an average delta-nucleon mass of 1.129 GeV (exp.val.=1.085 GeV). A similar set of parameters has been used to compute structure functions [8] and form factors [9].

The quark matter (QM) phase is characterized by a constant value of the scalar fields and by using plane waves to describe the quarks. The total energy of QM in the mean field approximation reads

$$\begin{aligned}E_{\mathrm{QM}} &= 6V\sum_{f=u,d,s}\int\frac{d\mathbf{k}}{(2\pi)^3}\sqrt{\mathbf{k}^2+m_f^2}\,\theta(k_F^f-k) \\ &+VU(\bar{\chi})+VW(\bar{\sigma},\boldsymbol{\pi}=0),\end{aligned} \tag{3}$$

where k_F^f is the Fermi momentum of quarks with flavour f.

We will employ the CDM model to describe the deconfined quark matter phase. The high-density matter in the interior of neutron stars is described by requiring the system to be locally neutral

$$\tfrac{2}{3}n_u-\tfrac{1}{3}n_d-\tfrac{1}{3}n_s-n_e=0, \tag{4}$$

where $n_{u,d,s,e}$ are the densities of the u, d and s quarks and of the electrons, respectively. Morover, the system must be in β-equilibrium, i.e. the chemical potentials have to satisfy the following equations:

$$\mu_d=\mu_u+\mu_e, \tag{5}$$

and

$$\mu_s=\mu_u+\mu_e. \tag{6}$$

Eqs. (4)–(6) have to be solved self-consistently together with field equations, at a fixed baryon density $n=n_u+n_d+n_s$.

To describe the hadronic phase, we employ a relativistic field theoretic model of the Walecka type [16], including protons and neutrons only. The parameters used to define the Lagrangian of the hadronic part are given in the work of Horowitz and Serot [17] and used recently by Knorren et al. [18], labelled HS81 in Ref. [18]. The hadronic phase is also required to

[1] Throughout this paper we set $G=c=\hbar=1$, where G is the gravitational constant.

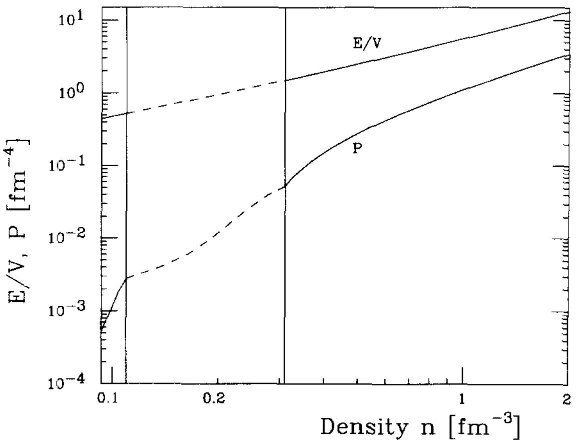

Fig. 1. Energy density and pressure as function of density n. The mixed phase begins at 0.11 fm^{-3} and ends at 0.31 fm^{-3}.

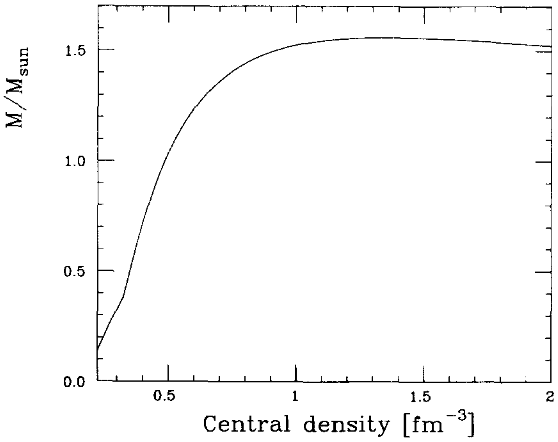

Fig. 2. $M/M_{\odot}$ as function of central density.

be in β-equilibrium, and the equations corresponding to Eqs. (4)–(6) at a fixed baryon density are

$$n_p = n_e, \tag{7}$$

and

$$\mu_n = \mu_p + \mu_e, \tag{8}$$

where the subscripts p and n refer to protons and neutrons, respectively.

For the mixed phase, we treat the multi-component system following recents works of Glendenning [19] and Müller and Serot [20]. This gives a mixed phase of quarks and hadrons which extends from 0.11 fm^{-3} to 0.31 fm^{-3}, whereas for higher densities matter is described by a deconfined quark phase only. In Fig. 1 we notice that the pressure exhibits a monotonic increase in the density region corresponding to the mixed phase. This should be contrasted to the case where only one conserved charge is present, as discussed in depth by Glendenning [19]. In the present work, we need to obey conservation of electric charge and baryon number.

From the general theory of relativity, the structure of a static neutron star is determined through the Tolman–Oppenheimer–Volkov equation, i.e.

$$\frac{dP}{dr} = -\frac{\{\rho(r) + P(r)\}\{M(r) + 4\pi r^3 P(r)\}}{r^2 - 2rM(r)}, \tag{9}$$

where $P(r)$ is the pressure and $M(r)$ is the gravitational mass inside a radius r. The equation of state discussed in Fig. 1 is then used to evaluate the total mass and radius of the neutron star. At very low densities ($0 \leq \rho \leq 0.08$ fm^{-3}), the model for the pure hadronic phase gives a negative pressure. At these densities, we link therefore our EOS with that of Malone et al. [21]. The resulting mass and radius exhibit only a weak dependence on the structure of the EOS at very low densities. The resulting mass is shown in Fig. 2. With the CDM we obtain a maximum mass $M_{\max} \approx 1.59 M_{\odot}$ and a radius of 10.5 km at a central density corresponding to approximately 7 times nuclear matter saturation density, in good agreement with the experimental values for the mass [3,4]. However, considerations about the maximum mass of a neutron star are not sufficient to discriminate between various equations of state, such as those derived within non-relativistic and relativistic baryonic many-body theories [22,23] or those employing approaches similar to the present work [19]. It is worth comparing with the work of Glendenning [19], which differs from ours in the model used for the pure quark phase. In Ref. [19] the MIT bag model is used, with masses for u and d quarks set to zero, while the mass of the s quark is set to 150 MeV. In the CDM, the masses of the u and d quarks are of the order of 100 MeV for all densities of interest. Another important point differentiating the two models is the vacuum pressure, which in the MIT model is of the order of 150 MeV and in the CDM is $\sim$ 50 MeV. This yields a rather different compo-

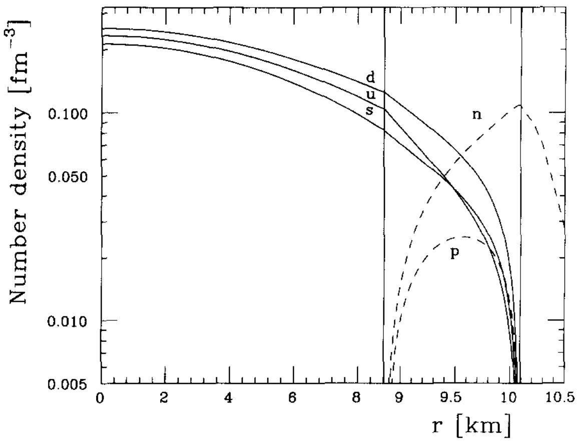

Fig. 3. Baryon and quark composition of a neutron star with central density 0.7 fm^{-3}, mass of $1.41 M_\odot$ and radius R = 10.52 km as function of the distance from the center. To help reading the figure, a different length's scale has been used where the mixed phase is formed.

sition of a neutron star compared with the results of Ref. [19]. In Fig. 3 we show the baryon and quark composition of a neutron star with central density 0.7 fm^{-3}, mass of $1.41 M_\odot$ and radius $R = 10.52$ km, obtained with the CDM model. One observes that the core of the star is composed of quark matter only, with a mixed phase which extends from 8.4 km to 10.1 km, and a crust region of pure baryonic matter. The structure of our star is therefore substantially different from that obtained using the MIT model, where the mixed phase encompasses most of the volume of the star, see Fig. 8 of Ref. [19], and the pure quark matter phase is never reached. In the results displayed in Fig. 3, the pure quark phase occupies half of the total volume, while the mixed phase occupies approximately 0.4 of the total volume. The deconfinement transition turns out to be much smoother in the CDM than in the MIT. Actually, there is the possibility that the transition in the CDM becomes a smooth crossover, if one considers correlations beyond the mean-field approximation [24].

A more stringent test to ascertain the validity of the various models is the computation of the cooling time of the neutron star. The composition of the star is crucial for neutrino and antineutrino emission, which can be responsible for the rapid cooling of neutron stars (URCA mechanism). In traditional scenarios of non-relativistic and relativistic nuclear physics the so-called direct URCA process can start at large densities only, of the order of 0.5–0.7fm^{-3} [22,25]. Various modified URCA processes have therefore been considered in more traditional studies of neutron star cooling. It is however an open question whether approaches based on baryonic degrees of freedom only are applicable at densities of the order of 0.5–0.7fm^{-3}. It is therefore of interest to see whether the direct URCA process can start if the interior of the star consists of quark matter. We discuss now this process considering quark matter described by the CDM. In the interior of the star shown in Fig. 3, where also strange quark matter is present, the relevant reactions are:

$$d \to u + e^- + \bar{\nu}_e, \tag{10}$$

$$e^- + u \to d + \nu_e, \tag{11}$$

$$s \to u + e^- + \bar{\nu}_e, \tag{12}$$

$$e^- + u \to s + \nu_e. \tag{13}$$

To conserve momentum in the reactions, the following inequalities have to be satisfied:

$$|k_F^u - k_F^e| \le k_F^d \le k_F^u + k_F^e, \tag{14}$$

$$|k_F^u - k_F^e| \le k_F^s \le k_F^u + k_F^e. \tag{15}$$

For densities larger than 0.53 fm^{-3}, conditions (14) are satisfied and the direct URCA mechanism involving only u and d quarks can start. Conditions (15) are satisfied only for densities larger than 1.4 fm^{-3}. At lower densities, we have various modified URCA processes with quarks, and at densities below 0.31 fm^{-3}, also the corresponding modified URCA processes with protons and neutrons. The direct URCA mechanism involving strange quarks is suppressed by a factor $\sin^2\theta_c \simeq 0.05$ with respect to the previous process, where θ_c is the Cabibbo angle.

Here we focus on the direct URCA process for quarks. We compute the neutrino and antineutrino luminosity, using the ultrarelativistic expansion for the chemical potentials [12]. This approximation is reasonable because the ratio m_q/k_F is approximately equal to 0.25. One gets for the total luminosity [12]

$$\epsilon = \frac{457}{1680} G_F^2 \cos^2\theta_c m_d^2 f k_F^u (k_B T)^6, \tag{16}$$

where $f = 1 - (m_u/m_d)^2 (k_F^d/k_F^u) - (m_e/m_d)^2 \times (k_F^d/k_F^e)$. To obtain the characteristic cooling time we equate the energy loss per unit volume to the rate of change of thermal energy per unit volume $\tau = c_V T/\epsilon$. Here the heat capacity of the QM is $c_V = \sum_{f=u,d,s} m_f k_F^f k_B^2 T$. We get $\tau = C$ 1 day$/T_9^4$, where T_9 is the temperature measured in units of 10^9 K and C is a constant ranging from 0.5 to $\sim$ 10 going from heavy to light neutron stars. The cooling time obtained considering quark matter described by the MIT model is roughly one order of magnitude smaller, $\tau \simeq 1$ hour$/T_9^4$ [12]. However, in order to compare with observation, the structure of the star has to be computed in details. In particular the possible presence of superfluidity in the interior has to be considered. The superfluid would suppress the $\nu, \bar{\nu}$ emissivity and would allow for reheating through friction with the crust. There are also indications [26,27] that temperatures of young ($\sim 10^4$ years old) neutron stars lie below that obtained through the so-called modified URCA processes. One has also to note [28] that the modified URCA processes are weakly dependent on the mass of the star, i.e. on the central density, while faster cooling mechanisms like the above direct URCA processes are in general strongly dependent on it. Thus, the detection of two coeval stars, whose temperatures differ by a factor of the order of 2 or larger would allow to distinguish between traditional cooling scenarios, like those discussed by Page [28], and more exotic ones like the above direct quark URCA reactions. Such a huge variation in the temperature of coeval stars would indicate the presence of a threshold in the cooling mechanism, triggered by the density of the star [29].

In summary, the principal properties of a neutron star, described using the CDM, are in agreement with observations. When comparing with the MIT model, one should also consider the very recent result from lattice QCD studies [30], indicating that at finite density the deconfinement transition is a smooth crossover and that at low temperatures chiral symmetry remains broken at all densities. Both these indications point in the direction of the CDM.

This work has been supported by the Istituto Nazionale di Fisica Nucleare (INFN) , Italy, the Istituto Trentino di Cultura, Trento, Italy, and the Research Council of Norway. We are also indebted to Profs. L. Caneschi, D. Mukhopadyay and E. Østgaard for useful comments on the manuscript.

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