Neutron star properties with in-medium vector mesons

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Abstract. We explore the impact of in-medium modification of the properties of
vector mesons on the nuclear equation of state and neutron star properties. It is found
that in-medium modifications stiffen the nuclear equation of state considerably. If this
feature has its correspondence in the full treatment of dense hadronic matter, then
very little room is left for the existence of exotic phases like quark matter or boson
condensates in the centers of neutron stars of canonical mass.

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1. Introduction

The exploration of the properties of in-medium hadrons is a topic of very great current interest. This is reflected by the number of experiments either planned or recently performed which target at the determination of medium modification of hadrons, especially of $K^\pm$ and $\rho$ mesons. The first results of the CERES and HELIOS collaborations show a significant enhancement of the production of low-mass lepton pairs \cite{1, 2} in relativistic nucleus-nucleus collisions, compared to the yield that one expects from proton-proton collisions. Since these lepton pairs are direct signals from the decay of vector mesons within the hot reaction zone, this enhancement points toward modifications of the masses and/or widths of vector ($\rho$ and $\omega$) mesons in a dense hadronic environment \cite{3, 4, 5}.

Medium modifications of mesons, as described just above, are generally ignored in standard treatments of hot and dense hadronic matter \cite{6}. In the framework of such treatments, the nuclear interaction is described through the exchange of mesons whose properties are entirely medium independent. The most important of these mesons are the $\pi$, $\sigma$, $\rho$ and $\omega$ mesons. It seems to be a general feature that standard treatments fail to reproduce the observed enhancement in the production of low-mass lepton pairs \cite{7}. This appears to be different for theoretical treatments which account for in-medium modifications of vector mesons.

In this paper we introduce two such treatments, one based on the Brown-Rho scaling scheme while the other constitutes a novel approach based on the techniques of effective nuclear field theory, which are used to computed corrections to the nuclear equation of state (EOS) that originate from the in-medium modifications of $\rho$ and $\omega$ vector meson properties. These models for the equation of state are then used to determine several key properties of neutron stars, such as the limiting stellar mass, the mass-radius relationship, and the Keplerian velocity. These quantities are known to be very sensitive to variations in the nuclear equation of state \cite{3} and, therefore, serve to test as to whether the in-medium vector-meson modifications computed for the two theoretical treatments are compatible with solid astrophysical data on neutron stars.

2. Theoretical treatment of vector mesons in matter

2.1. Choice of Lagrangian

In order to study the medium modifications on vector mesons, described in section 1, we assume that the interactions producing these modifications are independent of the interactions used in the Walecka lagrangian, so we may take them into account by only modifying the meson properties themselves. For the nuclear interaction we adopt the non-linear Walecka model. In this model the basic degrees of freedom are the nucleon $N$, the scalar self-interacting $\sigma$ meson, and the $\omega$ and $\rho$ vector mesons. The lagrangian is given by

$$\mathcal{L} = \bar{\Psi} \gamma^\mu (i \partial_\mu - g_\omega \omega_\mu) \Psi - \bar{\Psi} (m_N - g_\sigma \sigma) \Psi$$
\[-\frac{1}{4}(\partial^\nu \omega^\mu - \partial^\mu \omega^\nu)(\partial_\nu \omega_\mu - \partial_\mu \omega_\nu) + \frac{1}{2}m_\omega^2 \omega_\mu \omega^\mu \]
\[+ \frac{1}{2}(\partial_\nu \sigma \partial^\nu \sigma - m_\sigma^2 \sigma^2) - \frac{1}{3}bm_N(g_\sigma \sigma)^3 - \frac{1}{4}c(g_\sigma \sigma)^4 \]
\[-\frac{1}{4}(\partial^\nu \rho^\mu - \partial^\mu \rho^\nu)(\partial_\nu \rho_\mu - \partial_\mu \rho_\nu) + \frac{1}{2}m_\rho^2 \rho_\mu \rho^\mu \]
\[\text{where } \Psi \text{ denotes the nucleon fields, and } g_\sigma, g_\omega, g_\rho, b, \text{ and } c \text{ are the meson-nucleon coupling constants.} \]

The equations of motion that follow from these equations are solved in the mean-field approximation, where the meson fields are substituted by their classical expectation values. The parameters of the model \((g_\sigma, g_\omega, g_\rho, b, \text{ and } c)\) are fitted to the binding energy \((-16 \text{ MeV})\), nuclear incompressibility \((K = 240 \text{ MeV})\) and effective nucleon mass \((m_N^* = 0.8 \ m_N)\) at the saturation density \((\rho_0 = 0.168 \text{ fm}^{-3})\) of infinite nuclear matter. (A soft equation of state was predicted recently by a novel many-body approach that is based on the principles of chiral perturbation theory.) In passing, we mention that we ignore possible medium modifications of the properties of the scalar \(\sigma\) meson. Being a Goldstone boson, it is not clear how the properties of this meson may change in dense hadronic matter. Application of the Brown-Rho scaling scheme to the \(\sigma\)-meson mass, for instance, leads to an over-binding of nuclear matter. Since we are mainly interested in the high-density part of the equation of state of hadronic matter, which is dominated by the exchange of vector mesons among the nucleons, it is rather safe for our purposes to ignore medium effects on the \(\sigma\) meson.

2.2. In-medium modifications of vector meson properties

Next we turn to the two alternative models employed in this paper to explore the in-medium properties of \(\rho\) and \(\omega\) mesons in dense hadronic matter. The first model is based on the familiar Brown-Rho scaling according to which the masses of vector mesons and nucleons in a hadronic medium scale as

\[
\frac{m_\omega^*(\rho)}{m_\omega} = \frac{m_\rho^*(\rho)}{m_\rho} = \frac{m_N^*(\rho)}{m_N},
\]

where the asterisks denotes the particle masses in the medium. For the motivation of this scaling law we refer to the original literature. The effective mass of the nucleon at a given density, \(m_N^*(\rho)\), is taken from the Walecka model,

\[
m_N^*(\rho) = m_N - g_\sigma < \sigma >,
\]

with \(< \sigma >\) the mean-field ground-state expectation value of the \(\sigma\) meson. The second model which we study here is a novel approach based on the techniques of effective nuclear field theory. In the framework of this model, a low-density expansion is performed in order to establish a connection between the meson-nucleon scattering amplitudes and the properties of mesons in nuclear matter. This scheme leads to a systematic expansion for the in-medium self energy of a meson (as well as any other particle) in terms of the corresponding vacuum scattering amplitudes. The
vector-meson–nucleon scattering amplitudes are not directly related to experimental observables. Instead they are determined indirectly in a coupled-channel scheme where the $\rho N$ and $\omega N$ channels enter in intermediate and final states of measured processes. The parameters of this theory are fixed by fitting the available meson-nucleon scattering data in the relevant energy range. We employ these scattering amplitudes to construct the vector-meson self energies in nuclear matter to leading order in density.

The effective field theory provides us with the scattering lengths and spectral functions of vector mesons as a function of the density. For $\rho$ and $\omega$ vector mesons, the $\rho$–$N$ and $\omega$–$N$ scattering lengths are defined as $\langle V = \rho, \omega \rangle$

$$a_{VN} = f_{VN}(\sqrt{s} = m_N + m_V),$$

which leads to

$$a_{\rho N} = (-0.1 + 0.6 i) \text{ fm} \quad \text{and} \quad a_{\omega N} = (-0.5 + 0.2 i) \text{ fm}.$$  

To lowest order in density, this corresponds to the following in-medium modifications of the vector meson masses and their widths at nuclear matter density:

$$\Delta m_\rho \simeq 10 \text{ MeV}, \quad \Delta m_\omega \simeq 50 \text{ MeV}, \quad \Delta \Gamma_\rho \simeq 120 \text{ MeV}, \quad \Delta \Gamma_\omega \simeq 40 \text{ MeV}.$$  

We stress that the coupling of the vector mesons to baryon resonances below threshold, which is reflected in the strong energy dependence of the scattering amplitudes, cannot be neglected. One should therefore use the whole vector-meson spectral functions as done in this paper in order to achieve a most reliable description. As it turns out, however, application of the simple mass shift scheme for the in-medium effects on vector mesons leads to results that are rather similar to those obtained by using the full treatment, based on medium dependent spectral functions.

As a side-remark we mention that the validity of these two schemes adopted to include in-medium modifications in the equation of state is naturally limited to moderately compressed hadronic matter. The extent to which they are applicable to very highly compressed hadronic matter as existing in the centers of very heavy neutron stars is an open issue. The situation looks quite promising, though, for neutron stars of average mass, $M \simeq 1.4 \, M_\odot$, whose central densities may be just a few times higher than the density of ordinary nuclear matter, depending of the stiffness of the equation of state (cf. section 4).

3. Numerical outcome

We begin our discussion of the impact of in-medium modifications of vector mesons on the nuclear equation of state and neutron star properties with fig. 1 which shows the spectral functions of $\rho$ and $\omega$ mesons for three selected sample densities. These results are complementary to the recent calculations of ref. [12]. Taking into account the photon induced reactions via a generalized vector meson dominance the latter paper finds weaker medium effects for the $\rho$-meson than established here. In the next step we apply the two schemes introduced in section 2.3, i.e. Brown-Rho scaling and modified
Figure 1. Spectral functions of $\rho$ and $\omega$ mesons in nuclear matter at densities $\rho = \rho_0$ and $3\rho_0$ compared to those in vacuum ($\rho = 0$).

Figure 2. Effective nucleon mass in isospin-symmetric nuclear matter determined for three scenarios: no in-medium modifications of vector mesons (solid line), medium modifications of vector mesons computed for the spectral function method (dashed) and Brown-Rho scaling scheme (dotted line).

spectral function method, to determine the medium induced modifications of vector mesons and calculate the effective nucleon mass in matter, $M^*$, as well as the nuclear equation of state over a considerable range of densities. The outcome is shown in figs. 2 and 3, respectively. It is evident from fig. 2 that in-medium effects do not alter the overall density dependence of $M^*$ in dense hadronic matter: the effective nucleon mass drops monotonically with increasing density, as known from standard calculations [6]. At the density of ordinary nuclear matter, $\rho_0$, $M^*$ is basically unchanged from the value where in-medium effects on the vector mesons are ignored. Deviations however begin to show up at densities that are three times $\rho_0$ or higher and grow monotonically with density. This feature, together with the pronounced stiffening of the equation of
Figure 3. Equation of state of isospin-symmetric nuclear matter. The labeling of the curves is the same as in fig. 2.

state caused by the in-medium effects, shown in fig. 3, renders such modifications very important for neutron star properties. We will come back to this issue in greater detail in section 4. The stiffening of the equation of state is a consequence of the fact that both energy density and pressure depend on the vector meson masses as $\propto m^{-2}$. This proportionality characterizes the high-density regime of the equation of state, which is dominated by the exchange of vector mesons. Quantitatively, the in-medium vector-meson masses $< m_{V}^{-2} >$ were computed self-consistently, with the weights entering in the expectation values given by the spectral functions.

4. Neutron star structure

In this section we explore the implications of in-medium modifications of vector mesons for the structure of neutron stars. The properties of such objects provide important constraints on the behavior of dense matter, for any model for the nuclear equation of state which fails to accommodate neutron star masses of at least the mass of the Hulse-Taylor radio pulsar PSR 1913+16, $(1.444 \pm 0.003) M_\odot$, and the rotational periods of the two fastest presently known neutron stars, 1937+21 and 1957+20, each one rotating at 1.6 ms (620 Hz), can definitely be ruled out as a viable candidate for the true equation of state [6].

From model calculations, it is known that neutron stars possess rather complex interior structures [8]. Only in the most primitive conception, a neutron star is constituted from neutrons. At a more accurate representation, a neutron star contains neutrons ($n$) and a certain number of protons ($p$) in chemical equilibrium,

$$\ n \leftrightarrow p + e^- + \bar{\nu},$$

(7)
which implies for the corresponding chemical potentials that

$$\mu_n = \mu_p + \mu_e + \mu_{\bar{\nu}}. \quad (8)$$

Since neutrinos do not accumulate in neutron stars older than a few seconds, we set \(\mu_{\bar{\nu}} = 0\). The electric charges of the protons in the star must be balanced to very high precision by electrons (\(e^-\)), which leads to the additional constraint for the densities of protons and electrons

$$\rho_p = \rho_e. \quad (9)$$

If the particles in the center of a neutron star would arrange themselves in a way other than dictated by eq. (9), gravity would not be able to bind a neutron star.

Figure 4 shows the equation of state of neutron star matter computed from the lagrangian of eq. (1) subject to the two neutron star matter constraints (8) and (9). As for the nuclear matter case shown in fig. 3, the free-particle case clearly provides the least pressure of all three models. Yet the equation of state is stiff enough to accommodate neutron stars as heavy as about 2 \(M_\odot\), as will be discussed in more detail below. Another issue concerns the relative proton fraction in neutron star matter, shown in the upper-right panel of fig. 4, which is of central importance for the cooling of neutron stars. As pointed out in [13], if \(\rho_p/\rho\) becomes larger than the critical fraction of about 11%, the so-called direct Urca process,

$$n \rightarrow p + e + \nu_e, \quad (10)$$

where neutrons can transform to protons and electrons without the need of a bystander particle, becomes possible in neutron stars. Otherwise neutron stars were to cool via the less efficient standard Urca process,

$$n + n \rightarrow n + p + e + \nu_e. \quad (11)$$

The direct Urca process is crucial for the temperature evolution of neutron stars as it speeds up the cooling of such objects considerably in comparison with the standard Urca process. Our models for the equation of state predict that the process in (10) can take place at densities around 2.3 \(\rho_0\) if in-medium effects on vector mesons are ignored. Accounting for them, on the other hand, brings this threshold down to densities as low as 1.5 \(\rho_0\). Because of the rather flat density profiles in the inner parts of neutron stars, this implies that the cores in neutron stars which exhibit the direct Urca process are several kilometers bigger for an equation of state accounting for in-medium effects. As an example of a neutron star that may require very fast cooling as driven by the direct Urca process (10) we quote pulsar PSR 1929+10 [6].

The stiffness/softness of the equation of state above nuclear matter density intimately manifests itself in the interplay between radius, mass, and central density of a neutron star, as discussed next. We begin with the mass-radius relationship of non-rotating neutron stars computed by solving the Tolman-Oppenheimer-Volkoff equations, which describe the properties of spherically symmetric stars that are in general relativistic, hydrostatic equilibrium [8]. The outcome is shown in fig. 5, which
reveals that our collection of equation of states predicts limiting gravitational neutron star masses between about $2 \, M_\odot$ and $3 \, M_\odot$, with the high-mass end obtained for the equations of state that include in-medium effects. This range accommodates even the heaviest neutron stars that may exist in stellar binary systems. Examples of which are the X-ray pulsar Vela X-1, whose mass is $M = 1.87^{+0.23}_{-0.17} \, M_\odot$ [14], and the burster Cygnus X-2 whose mass is $M = (1.8 \pm 0.4) \, M_\odot$ [15]. Indications for the possible existence of very heavy neutron stars, with masses around $2 \, M_\odot$, may also come from the observation of quasi-periodic oscillations in luminosity in low-mass X-ray binaries [16]. These mass values are larger than the typical $(1.36 \pm 0.08) \, M_\odot$ masses found in neutron star binaries, presumably due to accreted matter. It is evident that neutron stars that heavy, provided the mass determinations turn out to be robust, would require extremely stiff equations of state. The inclusion of in-medium effects of vector mesons would alter the equation

Figure 4. Equation of state of chemically equilibrated neutron star matter. The labeling of the curves is the same as in fig. 2.
of state in the right direction.

Another very important conclusion follows from the general feature that stiff equations of state make neutron stars less dense [6]. This effect can be quite dramatic, depending on the stiffness of the equation of state. As shown in fig. 4, the models computed in this paper predict central densities on neutron stars of canonical mass of around $3 \rho_0$ if no in-medium effects are taken into account. This value drops down to $\sim 1.5$ to $2 \rho_0$ if in-medium effects are taken into account. Therefore, if the medium effects as computed in this paper have their correspondence in the full treatment of dense hadronic matter, then the consequences for the composition of neutron stars of masses $M \sim 1.5 M_\odot$ would be quite dramatic, for it leaves basically no room for the existence of novel degrees of freedom, such as quark matter or boson condensates, in the centers of such objects. Only neutron stars with masses close to their limiting masses (solid dots in fig. 5) may possibly hide these novel phases of matter.

Rapid neutron star rotation constitutes another important constraint on the stiffness/softness of the nuclear equation of state. The two most rapidly rotating neutron stars presently known, PSR 1937+21 and PSR 1957+20, rotate at 1.58 ms, which corresponds to about 620 rotations per second. Such high rotation rates constitute a considerable fraction of the Kepler frequency, $\Omega_K$, at which mass shedding from the star’s equator sets it. Evidently, mass shedding sets an absolute limit on rapid rotation which cannot be overcome by any stably rotating object. In order to determine $\Omega_K$ for a given model for the equation of state one has to go beyond the Tolman-Oppenheimer-
Figure 6. Neutron star mass versus central density, computed for the EOSs of this paper. The arrows indicated the rotation-induced mass increase due to rotation at the Kepler frequency, $\Omega_K$. The solid dots denote the heaviest star of each sequence.

Volkoff treatment and solve Einstein’s field equations

$$R^{\mu \nu} - \frac{1}{2} g^{\mu \nu} R = 8 \pi T^{\mu \nu}(\rho, P(\rho)),$$

(12)

self-consistently in combination with the general relativistic expression describing the onset of mass-shedding at the star’s equator [6],

$$\Omega_K = \omega + \frac{\omega'}{2 \psi'} + e^{\nu-\psi} \sqrt{\frac{\nu'}{\psi'} + \left(\frac{\omega'}{2 \psi'} e^{\psi-\nu}\right)^2}.$$  

(13)

The quantities $R^{\mu \nu}$, $g^{\mu \nu}$, and $R$ denote the Ricci tensor, metric tensor, and Ricci scalar (scalar curvature), respectively. The dependence of the energy-momentum tensor $T^{\mu \nu}$ on the equation of state is indicated in eq. (12). The quantities $\omega$, $\nu$, and $\psi$ in eq. (13) denote the frame dragging frequency of the local inertial frames, and the time and space-like metric functions, respectively. The primes denote derivatives with respect to Schwarzschild radial coordinate, and all functions on the right are evaluated at the star’s equator. All the quantities on the right hand side of eq. (13) depend also on $\Omega_K$, so that it is not an equation for $\Omega_K$, but a transcendental relationship which the solution of the equations of stellar structure, resulting from eq. (12), must satisfy if the star is rotating at its Kepler frequency.

The numerical outcome for $\Omega_K$ is shown in fig. 7, where we plot $\nu_K (\equiv 2\pi/\Omega_K)$ as a function of rotational stellar mass, $M$. For neutron stars of canonical mass, $M \sim 1.4 M_\odot$, one reads off from this figure that such stars can perform up to $\sim 1000$ rotations per second before breaking up into pieces. This comfortably accommodates
the spin frequencies of the two fastest rotating neutron stars presently known. Rapid rotation in combination with stellar masses provides a double constraint on the equation of state, since the successful model for the nuclear equation of state must account for the smallest observed rotational neutron star periods as well as the heaviest neutron star masses. The constraints on the equation of state become the more stringent the smaller a neutron star’s rotational period and the larger its mass. Searches for such neutron stars are being performed at several radio observatories. It is evident from fig. 7 that only very compact neutron stars, compressed to small radius values, will be able to withstand rapid rotation rates that are significantly higher than 600 Hz. Neutron stars at or close to the limiting mass of a given stellar sequence are such candidates. Depending on stiffness/softness of the equation of state, these may rotate at frequencies as large as 1500 to 1700 Hz, which corresponds to rotational periods between 0.7 and 0.4 milliseconds, respectively. The only other class of stars understood to withstand such rapid rotation are the strange stars, which should replace neutron stars if 3-flavor strange quark matter is the true ground-state of the strong interaction \cite{17, 18}, which, despite of many years of research, is still an open issue. As a final point, we point out that rapid rotation stabilizes a neutron star against gravitational collapse. Figure 6 reveals that the mass that can be supported due to rapid rotation may be up to $\sim 20\%$ higher than non-rotating mass value. It is striking that the rotation-induced mass increase is accompanied by a reduction in central star density, contrary to what one would expect from simple mass loading onto a star. The explanation is provided by the centrifugal
pressure that builds up inside a rotating star. For rapidly spinning neutron stars, this contribution is quite significant so that considerably less interior pressure (typically 30 to 40%, as can read off from fig. 3 in combination with fig. 4) must be provided by the equation of state itself. As already mentioned in connection with the discussion of the properties of non-rotating neutron stars, lower densities at the center of a neutron star rival with exotic particle processes predicted for high-density matter, like the formation of boson condensation and the transition into quark matter.

5. Conclusions

This paper presents an investigation of the effect of in-medium modification of vector mesons on the nuclear equation of state and the properties of neutron stars. The latter serve to test the compatibility of in-medium effects with observed data. We find that in-medium modifications reduce effectively the masses of vector mesons which in turn stiffens the equation of state considerably. This has several intriguing implications for the structure and composition of neutron stars. Firstly, because of the stiffening of the equation of state, even the most massive neutron stars, like Vela X-1 ($M = 1.87^{+0.23}_{-0.17} M_\odot$) and the burst source Cygnus X-2 ($M = (1.8 \pm 0.4) M_\odot$), can be easily supported by equations of state accounting for medium-modified vector meson properties. Secondly, knowledge of the limiting neutron star mass is key in order to identify black hole candidates. That is, if the mass of a compact companion of an optical star is determined to exceed the limiting mass of a neutron star, it must be a black hole. The limiting mass of stable neutron stars in our theory is between 2.6 and 2.8 $M_\odot$. Hence any binary heavier than these values would be low-mass black holes. The third striking point is that the computed neutron star models have rather low central densities, just a few times the density of ordinary nuclei for canonical neutron star masses around $M \sim 1.5 M_\odot$. If this should withstand more elaborate future treatments, it would leave basically no room for the existence of novel degrees of freedom such as quark matter or boson condensates in the centers of neutron stars. Such objects would then merely consist of chemically equilibrated neutrons and protons.

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