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On the possibility of rho-meson condensation in neutron stars

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ABSTRACT

We study the possibility of vector (ρ^-) meson condensation in dense matter subject to strong magnetic fields. For this purpose, we adopt a standard relativistic equation of state (GM3). We find that rho-meson condensates can appear in the core of the neutron star as the rho mass decreases with density and magnetic field. For reasonable values of the parameters, the rho condensate can appear in a neutron star at 4.4 times the normal nuclear matter density. This number guarantees a sizeable portion of the star to have a ρ-condensed phase.

Key words: dense matter – equation of state – stars: magnetic field – stars: neutron.

1 INTRODUCTION

The study of strongly interacting matter at high densities and/or temperatures is one of the central themes of modern nuclear physics. From the experimental side, the main approaches to learn about matter under these conditions are the study of relativistic heavy-ion collisions (HIC) and observations of neutron stars (NSs), where the former approach aims at studying high-temperature and the latter one high-density and low-temperature matter. In addition, the future experiments at GSI/FAIR with beam energies ≤30 GeV per nucleon and the beam energy scan at RHIC aim to study the properties of matter not only at high temperature but also at comparatively high density.

It is expected that at high density the spontaneously broken chiral symmetry, characterized by a large quark condensate, is at least partially restored. However, a clear observable signature of this effect is still not well established. From the theory side, an early simplified conjecture proposed by Brown and Rho (Brown & Rho 1991) argued that hadrons (except for the pseudo-Goldstone bosons like pions) experience a mass reduction in nuclear matter, which is proportional to the in-medium quark condensate. More recent calculations, using QCD sum rules (Hatsuda & Lee 1992), quark-meson models (Saito & Thomas 1994) and hadronic models of vacuum polarization (Jean, Piekarewicz & Williams 1994) also suggest such a mass reduction. However, a full understanding of the restoration of chiral symmetry in dense matter remains an open and much-discussed topic.

More direct evidence of a potential mass reduction of vector mesons, the enhancement in the production of low invariant-mass dileptons in HIC has been investigated extensively as measured by the CERES experiment at the CERN-SPS (Agakichiev et al. 1995). Various model studies ranging from simple thermal models to more detailed transport calculations predicted enhanced dilepton production (Cassing, Ehehalt & ko 1995; Koch & Song 1996; Srivastava et al. 1996; Bratkovskaya & Cassing 1997). One of the conjectures which explains such enhanced dilepton production in HIC suggested the reduction of the in-medium masses of the vector mesons. The theoretical results were consistent with experimental data. However, later dynamical studies hinted that the earlier studies overestimated the effect (Cassing et al. 1998). The enhancement in dilepton production due to vector meson mass reduction also differed from experiment to experiment [consistent at SPS energies but not with DLS results (Bratkovskaya & ko 1999)]. The NA60 measurement of dilepton spectra, however, shows that there is a broadening in the rho-meson spectral function. This makes it very difficult for the actual peak to be located and, therefore, the medium dependent mass of the meson ρ is still not clear. Overall, the situation with respect to dilepton enhancement is still not unambiguously resolved. In addition, note that the dilepton studies sample very different conditions of temperature and density compared to the dense and cold matter of a neutron star (NS). As shown in an analysis of particle production within an extended relativistic mean-field approach, the masses of the hadrons are only shifted by about 10 per cent or less, nevertheless there are strong chances of the meson condensates to appear in dense and cold matter (Zschiesche et al. 2005).

More recent experiments of $\gamma - A$ (Trnka et al. 2005) reactions provided a clearer signature of an in-medium ω mass reduction. In the experiment by the TAPS collaboration (Trnka et al. 2005), the modification of the ω in nuclei was measured in photoproduction experiments, where its mass was found to be $m^*_\omega = 722 \pm 4$ MeV at $0.6\, n_0$ ($n_0 = 0.15 fm^{-3}$, the normal nuclear matter density), which is in the range of shifts of the rho-meson mass we assume in this

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investigation. Similar numbers were also found in 12 GeV photon-nuclear reaction by Naruki et al. (Naruki et al. 2006). The ω meson mass and quark-condensate were studied in more recent NJL model calculations (Huguet, Caillon & Labarsouque 2007), where a scaling behaviour was approximately recovered using constraints from the TAPS experiment. However, the behaviour of the ρ mass in the zero-temperature/high-chemical potential regime is still largely undetermined.

On the other hand, QCD exhibits exciting physics in a strong background magnetic field, since quarks are electrically charged and can be strongly affected by the field (Chernodub 2013). Strong magnetic field modify chiral symmetry breaking by increasing the quark-condensate (Schramm, Mueller & Schramm 1992a; Gusynin, Miransky & Shovkovy 1994). However, the strength of the magnetic field necessary to effect the strongly coupled systems is about $eB \sim m_\pi^2 \sim 3 \times 10^{18}$ G, where e is the charge of the electron, B is the magnetic field and m_π denotes the mass of pion. Quarks and antiquarks can form condensates in the presence of strong magnetic fields. For the quark-antiquark bound state with light quarks, i.e. for the rho-meson, strong magnetic fields can enhance the formation of a condensate.

As will be discussed later, the key idea lies in the fact that a sufficiently strong magnetic field can trigger an instability in the vacuum leading to condensates in specific quark channels, especially with respect to the charged vector mesons generating non-zero ρ condensates (Schramm et al. 1992a; Chernodub 2013). Huge magnetic fields are generated in peripheral of HIC, where the large nuclear charges and momenta magnify the magnetic field (Skokov, Illarionov & Toneev 2009). At LHC energies of 3.5 TeV, the strength of the magnetic field could be as high as 10^{20}–10^{21} G (Schramm, Mueller & Schramm 1992b). However, such a field only exists for a very short time and is restricted to a small volume.

On the other hand, the extreme conditions discussed above can occur naturally in NSs, where the nuclear density is several times the nuclear saturation density (n_0) and the magnetic field can be very strong (Ferrer et al. 2010; Dexheimer, Negreiros & Schramm 2012). The high density (high chemical potential) can affect the rho-meson mass and, with the aid of a strong magnetic field, a condensate can subsequently form.

The possibility of pion and/or kaon condensation in NSs has been investigated in numerous studies in the past. Since it was first suggested by Migdal (Migdal 1971, 1973), pion condensation and its impact on NS physics became the focus of intense discussion. There were calculations, both supporting and challenging a condensed state in the dense cores of compact stars. Similarly, for kaon (K^-) condensation (Kaplan & Nelson 1986), it was argued that since the electron chemical potential is an increasing function of density, whereas the effective (anti) kaon mass decreases with density, this allows condensation to set in at some density. Depending on the kaon-nucleon sigma term and the specific model, kaon condensation might occur at about 3–4 times saturation density. At this point, when the kaon energy becomes equal to the electron chemical potential, it is favourable for neutrons to decay to protons and kaons, rather than protons and electrons, giving rise to a kaon condensate. Such densities can easily be achieved in the cores of NSs and, therefore, condensation can take place. However, non-linear terms and the occurrence of hyperons tend to shift the onset of kaon condensation to higher densities (Mishra et al. 2010), beyond values reached in NSs.

One general problem present in meson condensation studies is its effect on the NS masses. The discovery of pulsars PSR J1614−2230 and PSR J0348+0432 (Demorest et al. 2010; Antonidis et al. 2013) with masses of approximately 2 $M_\odot$ puts severe constraints on the stiffness of the equation of state (EoS) for the core of NSs. Therefore, a potential onset of meson condensation is important, since (zero-momentum) condensates soften the EoS, thereby reducing the predicted maximum mass of the stars.

In this work, we study the possibility of rho-meson (ρ^-) condensation occurring inside an NS and look into the conditions which might make rho condensation possible. The first study regarding the possibility of rho condensate to appear in NSs was first considered in (Kolomeitsev & Voskresensky 2005; Voskresensky 1997), where they assumed Brown-Rho type hadronic mass modifications at high density. However, they did not consider the effect of magnetic field in their work. There are various aspects which increase the possibility of condensation in an NS environment. First, the extreme dense core which could strongly amplify a density-dependence of the meson mass. Secondly, as the NS is in a charge-neutral state, condensation of negatively charged particles sets in whenever their mass drops below the lepton Fermi energy, in striking contrast to the situation in an HIC, where there is no such effect. Finally, there is a possibility of strong extended magnetic fields in at least certain classes of NSs, called magnetars, in which a substantial effect on the condensation of a charged spin-1 particles can take place. The paper is structured as below. In the next section (Section 2), we discuss the effect of density and magnetic field on the rho mass in a dense environment. We show our results in Section 3. Finally in Section 4, we discuss our results and draw conclusion from them.

2 RHO-MESON MASS MODIFICATION BY DENSITY AND MAGNETIC FIELD

We use a standard relativistic mean field approach to study the possibility of rho-meson condensation. Within this approach, the nucleons interact through meson exchange represented by their mean field values. The scalar meson (σ) provides the attractive force, whereas the vector mesons (ω, ρ) generate repulsion. In order to investigate whether the rho-meson will condense in an NS, we assume a simple relation for the rho-meson mass. Certainly, in more extensive calculations a fuller study of density- (or field-) dependent masses of all involved hadrons should be performed. Here, in order to determine whether such a condensation could take place in principle, for simplicity, we adopt a linear dependence of the rho mass on the scalar field,

$$m_\rho^{\sigma *} = m_\rho - g\sigma, \tag{1}$$

where g is a dimensionless constant and $m_\rho = 776$ MeV is the vacuum mass of the rho-meson. This term effectively introduces a coupling term of the vector and scalar fields.

In the presence of a background magnetic field of strength B, the energy level $E_{\mathrm{n},S_\mathrm{x}}$ of a particle of mass m, charge e, and spin s in the Landau level n is given by (Skalozub 1985; Ambjorn & Olsen 1991; Schramm et al. 1992b; Chernodub 2010, 2013)

$$E_{\mathrm{n},S_\mathrm{x}}(p_\mathrm{x}) = \sqrt{{p_\mathrm{x}}^2 + m^2 + (2n - g_\mathrm{B} S_\mathrm{x} + 1)eB}, \tag{2}$$

where S_x and p_x are the spin projection and momentum projection on to the magnetic field axis, and g_B is gyromagnetic ratio of the particle which is taken to be 2 for the rho-meson (Samsonov 2003; Hedditch et al. 2007; Bhagwat & Maris 2008). Therefore, the energy squared of the lowest state for a charged rho-meson corresponding to $p = 0$, $n = 0$ and $S_\mathrm{x} = 1$ is

$$\epsilon_{0,1}^2(0) = m_{B\rho^-}^{*2} = m_{\rho^-}^2 - eB. \tag{3}$$

Taking these two effects into consideration, the energy squared becomes

$$\epsilon^2 = m^{*2}_{\rho^-} = (m_\rho - g\sigma)^2 - eB. \tag{4}$$

These equations point to the fact that, in principle, if the scalar field or magnetic field is high enough, the effective mass squared of the rho-meson can be negative and condensation can take place. However, for NSs, the situation is less restrictive. As mentioned above, the mass of the ρ^- only has to fall below the electron chemical potential, so that electrons can be replaced by negative rho-mesons for generating a charge-neutral system. In this case, we obtain an NS with rho-meson condensation.

In order to have a better idea about if and how the rho-meson condensation takes place in an NS, we have to adopt a specific model. Here, we choose a standard relativistic mean field description including electrons to ensure charge neutrality of matter. We choose the GM3 parametrization for our calculation as its EoS has frequently been used in the literature to describe nuclear matter in NSs (Glendenning & Moszkowski 1991). This EoS can generate 2 solar mass NSs, which is an important criterion. We solve the mean field equations at finite density including the additional term from equation (1). As this term does not affect isospin symmetric matter, the isospin-independent quantities of saturated matter for the GM3 parameters do not change. However, the GM3 value of the asymmetry energy ($a_{\rm sym} = 32.5$ MeV) changes. Therefore, while varying the field-dependence of the meson mass with the coupling g from equation (1), we accordingly adjust the $g_{N\rho}$ coupling of the nucleon to the rho-meson in order to maintain the original value of $a_{\rm sym}$. This conforms with the discussion in Heide et al. (1994), where an unphysical relative shift of the nuclear proton and neutron levels have been observed when the total mass of the rho-meson was generated by a coupling to the scalar field. This then led to a shift of the isospin behaviour in nuclear matter, which we avoid by rescaling the nucleon-rho coupling strength.

3 RESULTS

The results for stellar matter calculations are shown in Fig. 1. We plot the variation of the electron chemical potential and the effective mass of the rho-meson as a function of normalized baryon density. The dashed lines represent the rho-meson effective mass and the solid lines depict the electron chemical potential. In Fig. 1(a), the black lines show the respective values without any density or magnetic field effect ($g = 0$, $B = 0$). In this case, we find that there is no point of intersection between the lines, which means the rho-meson does not condense in this environment for any reasonable density.

The maximum bound of the strength of the magnetic field in NS is still not very well established. While magnetic fields as high as 10^{15}G have been measured at the surface of magnetars (Duncan & Thompson 1992; Paczynski 1992; Thompson & Duncan 1996; Melatos 1999), fields as high as 10^{16} have been measured inside them (Makishima et al. 2014). However, the upper bound in the cores of NSs is still not well understood. Most of the general relativistic calculations (Bocquet et al. 1995; Cardall, Prakash & Lattimer 2001; Mallick & Schramm 2014) show it to lie somewhere in between 10^{18}–10^{19} G. Similar values are also obtained from Virial theorem estimates employing a classical calculation, which was discussed recently in Potekhin & Yakovlev (2012). The exact value of the magnetic field and its structure depend strongly on the EoS and the region of the star. This limit also needs to be calculated taking into account general relativity and magnetic field modifications in the metric, not to mention magnetic field modifications to the EoS itself.

To have a maximum effect on the rho-meson by the magnetic field, we choose a magnetic field strength a bit on the higher side of the accepted value of a strength of 7×10^{18} G (5×10^5 MeV^2 in Lorentz–Heaviside natural units). The inclusion of the magnetic field ($B \neq 0$) shifts the curves but is still not able to generate a point of intersection (red lines in Fig. 1 a), which points to the fact that the magnetic field alone cannot give rise to rho-meson condensation in a compact star. In order to produce rho condensation solely due to a strong magnetic field, much higher values for the magnetic field are required (3–4 $\times$ 10^{19} G). Studies suggest that such high magnetic fields are difficult, if not impossible, to realize in an NS; however, they may locally appear for a short time during HIC. For rho-meson condensation to take place in NSs a rho-meson mass modification must be included. Taking this effect into account, we find that the blue lines (in Fig. 1 a) intersect at about 7.6 times nuclear saturation density (for $B = 0$). For such variation, we have assumed a vector–scalar coupling $g = -4$. Recent measurements of pulsar masses suggest that the central energy density of NSs might lie between 2–5 times nuclear saturation values (Demorest et al. 2010). On the other hand, a calculation assuming a soft low-density EoS coupled with stiff high-density EoS, showed that the maximum upper-bound

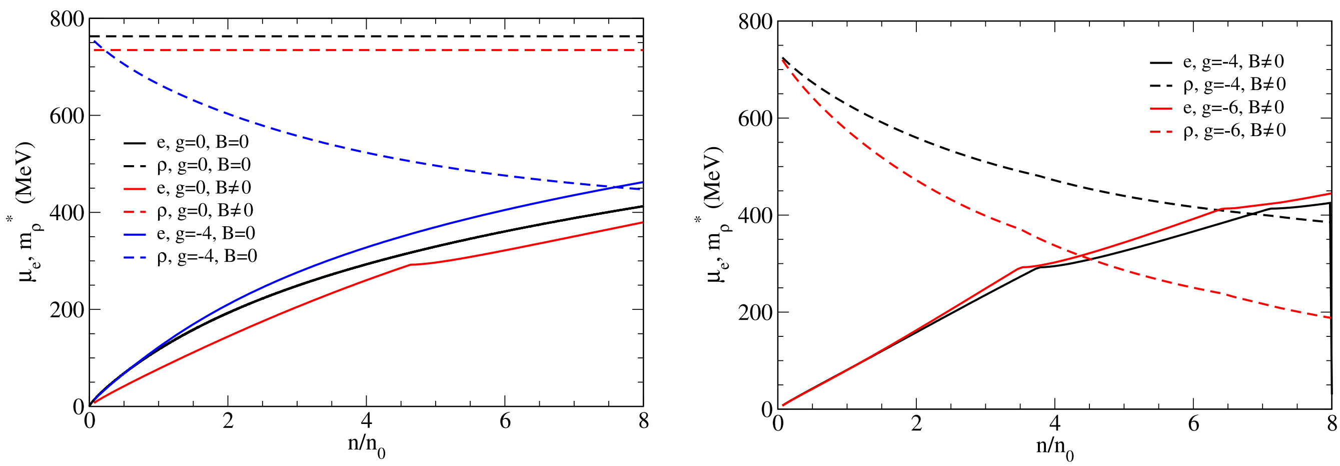

Figure 1. The electron chemical potential (solid lines) and effective ρ^- mass (dashed lines) are plotted as functions of normalized density. The points of intersection mark the density at which the rho-meson condensation appears.

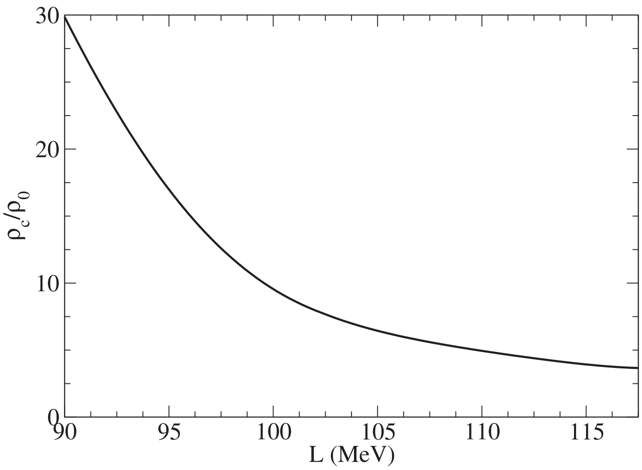

Figure 2. n_c/n_0 is shown as a function of the slope (L) parameter. The L parameter is dependent on the scalar coupling g.

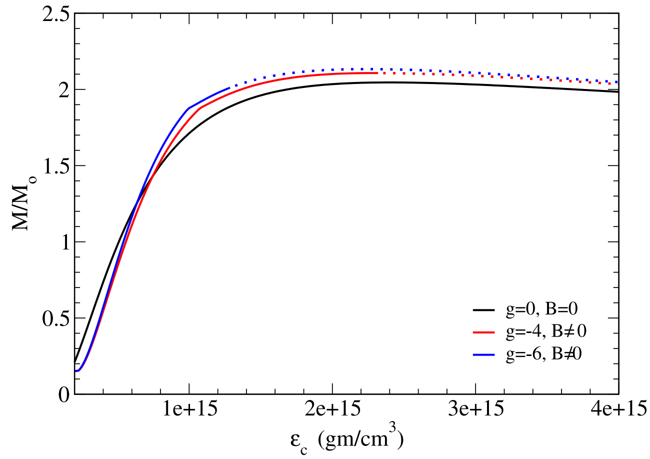

Figure 3. Sequence of stars for the GM3 EoS. The mass is shown as function of the central energy density. When both g and B are set to zero, there is no rho condensate inside the stars and the maximum mass achieved is 2.05 solar mass. When g and/or $B \neq 0$ the condensate appears. The dotted lines indicate stars that contain some amount of rho condensate.

density for a 2 solar mass pulsar is about $8n_0$ (Lattimer & Prakash 2005; Lattimer 2012). In order for condensation to occur at such densities one must consider the effects of density-dependence of the rho-meson mass and the effect of magnetic fields simultaneously.

In Fig. 1(b), we plot curves for the case in which both (in-medium and magnetic) effects are taken into account. With the above mentioned values of B and g, the ρ condensate sets in at approximately 6.9 times saturation density. However, if we now increase the value of g, i.e. assuming a larger rho mass modification due to in-medium effects, the condensate sets in at smaller densities. For $g = -6$, the condensate appears around 4.4 times nuclear saturation density. Therefore, for an NS with a central density of 6 times nuclear density, a rho-meson condensate appears in the core of the star and extends up to the radius where the nuclear density is 4.4 times nuclear density.

The lower limit of the effective rho-meson mass depends on the coupling constant g, i.e. the larger g, the lower the value of m^*_ρ in the dense matter. However, there is a lower bound to the rho-meson mass which is provided by nuclear matter properties, namely the symmetry energy slope L, defined as $L = 3\,\mathrm{d}\,a_{\rm sym}/\mathrm{d}\,n$, which describes the change of the asymmetry properties of matter with density. The value of L is expected to be in the range between 40–115 MeV at nuclear saturation density (Chen, Ko & Li 2005; Tsang et al. 2012; Lattimer & Lim 2013). In our case, the value of the L depends on g. In Fig. 2, we plot the normalized critical density for rho-meson condensation n_c (n_c/n_0) as a function of L. The curve clearly shows that n_c saturates at about $4\rho_0$ for large L. Increasing L (meaning increasing g) further does not affect n_c significantly. This shows that however large we make g, the condensate does not appear before the density of the star reaches 4 times nuclear saturation density for any reasonable nuclear matter properties. The figure also illustrates that the decrease in the rho-meson condensate critical density due to density dependent rho-meson mass corresponds to larger values of L (when compared to the original value of the model with fixed rho-meson mass). As the rho-meson enters the GM3-Lagrangian in a simple way through linear couplings to the nucleons, it is quite natural to assume that other models with an analogous treatment of the rho-meson would result into similar shifts of L. Therefore, models with very high original values of L do not yield a phenomenologically valid description of nuclear matter if one introduces strong rho-meson mass shifts like the one shown in equation (1).

To study how rho condensation impacts the macroscopic properties of an NS, we solve the Tolman–Oppenheimer–Volkov equations. In Fig. 3, we plot the sequence of stars obtained using the GM3 EoS. The black line represents the results for an NS where there is no ρ^- condensate and no magnetic field. The maximum mass achieved is about $2.05\,\mathrm{M}_\odot$. The red and blue curves show the sequence, where rho-meson condensation takes place. The solid parts of the curves represent stars which do not contain rho condensate, whereas the dotted parts of the curves indicate stars that have some amount of ρ^- condensate in their cores. For these curves, the magnetic field is set to zero or kept constant at $B = 7 \times 10^{18}$ G (as in Fig. 1). We find that as we increase g, the condensate appears much earlier, i.e. more and more stars of the sequence have a condensate region in their cores. Note that, we have determined the onset of condensation in stars but have not performed a full calculation of the star structure including a condensate. For $g = -4$, the condensation sets in just around the maximum mass ($M_{\rm max} = 2.1\,\mathrm{M}_\odot$), i.e. the stars which develop a condensate are already in the sequence of unstable stars. In the case of $g = -6$, the maximum star mass has a value of $M_{\rm max} = 2.13\,\mathrm{M}_\odot$, whereas the condensation sets in at 2 solar masses. Thus, assuming a drastic softening of the EoS, the largest possible shift of the maximum star mass is determined by the mass when condensation starts to occur, which, for this specific model, yields a shift downwards by $0.13\,\mathrm{M}_\odot$ for a coupling of $g = -6$, as can be inferred from Fig. 3. It is important to note that the effect of macroscopic magnetic fields on star masses has the opposite effect. Therefore, on one hand the condensation would try to bring the star mass down and on other hand the magnetic field would try to increase its mass. The exact amount by which the star masses shift with the magnetic field and condensation is highly non-trivial (Bocquet et al. 1995; Cardall et al. 2001; Mallick & Schramm 2014) and, for this reason, we chose not to discuss it numerically in this work.

4 SUMMARY AND DISCUSSION

To summarize, we studied the possibility of rho-meson condensation within a standard relativistic mean field approach. While not rigorously proving the existence of the condensate, we have shown that such a state can be achieved, especially in a stellar environment, using quite reasonable assumptions. We concluded that the appearance of the condensate requires a modification of the rho-meson mass in the dense medium. In addition, magnetic fields have a non-negligible effect in reducing the threshold for condensation further. For this to happen, the magnetic field has to be large, at least in the core region of the star; however, the exact upper limit of magnetic fields in the interior of an NS is still an open discussion.

We would like to mention at this stage that, although we had to use a specific model for obtaining numerical results, all the arguments we presented are quite generic and hold as well for other models. The actual numbers we have shown (condensation critical density, maximum mass shift due to condensation) will vary somewhat, but the qualitative nature of our result remains the same. One additional interesting consequence of the ρ-condensate would be the modification of the NS cooling, which will to be studied in more detail in the future. More general and microscopic quark-level based calculations of possible vector meson mass changes with density and their effects on the EoS can be interesting to explore and will be also presented in subsequent publications.

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REFERENCES

Agakichiev G. et al., 1995, Phys. Rev. Lett., 75, 1272
Ambjorn J., Olsen P., 1991, Phys. Lett. B, 257, 201
Antonidis J. et al., 2013, Science, 340, 448
Bhagwat M. S., Maris P., 2008, Phys. Rev. C, 77, 025203
Bocquet M., Bonazzola S., Gourgouhlon E., Novak J., 1995, A&A, 301, 757
Bratkovskaya E. L., Cassing W., 1997, Nucl. Phys. A, 619, 413
Bratkovskaya E. L., Ko C. M., 1999, Phys. Lett. B, 445, 265
Brown G. E., Rho M., 1991, Phys. Rev. Lett., 66, 2720
Cardall C. Y., Prakash M., Lattimer J. M., 2001, ApJ, 554, 322
Cassing W., Ehehalt W., ko C. M., 1995, Phys. Lett. B, 363, 35
Cassing W., Bratkovskaya E. L., Rapp R., Wambach J., 1998, Phys. Rev. C, 57, 916
Chen L.-W., Ko C. M., Li B.-A., 2005, Phys. Rev. C, 72, 064309
Chernodub M. N., 2010, Phys. Rev. D, 82, 085011
Chernodub M. N., 2013, in Kharzeev D., Landsteiner K., Schmitt A., Yee H.-U., eds, Lecture Notes in Physics, Vol. 871, Strongly Interacting Matter in Magnetic Fields. Springer-Verlag, Berlin, p. 143
Demorest P., Pennucci T., Ransom S., Roberts M., Hessels J., 2010, Nature, 467, 1081
Dexheimer V., Negreiros R., Schramm S., 2012, Eur. Phys. J. A, 48, 189
Duncan R. C., Thompson C., 1992, ApJ, 473, 322
Ferrer E. J., de la Incera V., Keith J. P., Portillo I., Springsteen P. P., 2010, Phys. Rev. C, 82, 065802
Glendenning N. K., Moszkowski S. A., 1991, Phys. Rev. Lett., 67, 2414
Gusynin V. P., Miransky V. A., Shovkovy I. A., 1994, Phys. Rev. Lett., 73, 3499
Hatsuda T., Lee S. H., 1992, Phys. Rev. C, 46, R34
Hedditch J. N., Kamleh W., Lasscock B. G., Leinweber D. B., Williams A. G., Zanotti J. M., 2007, Phys. Rev. D, 75, 094504
Heide E. K., Rudaz S., Ellis P. J., 1994, Nucl. Phys. A, 571, 713
Huguet R., Caillon J. C., Labarsouque J., 2007, Phys. Rev. C, 75, 048201
Jean H. C., Piekarewicz J., Williams A. G., 1994, Phys. Rev. C, 49, 1981
Kaplan D. B., Nelson A. E., 1986, Phys. Lett. B, 175, 57
Koch V., Song C., 1996, Phys. Rev. C, 54, 1903
Kolomeitsev E. E., Voskresensky D. N., 2005, Nucl. Phys. A, 759, 373
Lattimer J. M., 2012, Annu. Rev. Nucl. Part. Sci., 62, 485
Lattimer J. M., Lim Y., 2013, ApJ, 771, 51
Lattimer J. M., Prakash M., 2005, Phys. Rev. Lett., 94, 111101
Makishima K., Enoto T., Hiraga J. S., Nakano T., Nakazawa K., Sakurai S., Sasano M., Murakami H., 2014, Phys. Rev. Lett., 112, 171102
Mallick R., Schramm S., 2014, Phys. Rev. C, 89, 045805
Melatos A., 1999, ApJ, 519, L77
Migdal A. B., 1971, Sov. Phys. JETP, 61, 2209
Migdal A. B., 1973, Phys. Lett. B, 45, 448
Mishra A., Kumar A., Sanyal S., Dexheimer V., Schramm S., 2010, Eur. Phys. J. A, 45, 169
Naruki M. et al., 2006, Phys. Rev. Lett., 96, 092301
Paczynski B., 1992, Acta. Astron., 42, 145
Potekhin A. Y., Yakovlev D. G., 2012, Phys. Rev. C, 85, 039801
Saito K., Thomas A. W., 1994, Phys. Lett. B, 327, 9
Samsonov A., 2003, J. High Energy Phys., 0312, 061
Schramm S., Mueller B., Schramm A. J., 1992a, Mod. Phys. Lett. A, 7, 973
Schramm S., Mueller B., Schramm A. J., 1992b, Phys. Lett. B, 277, 512
Skalozub V. V., 1985, Sov. J. Nucl. Phys., 41, 1044
Skokov V., Illarionov A. Y., Toneev V., 2009, Int. J. Mod. Phys. A, 24, 5925
Srivastava M. K., Sinha B., Gale C., 1996, Phys. Rev. C, 53, R567
Thompson C., Duncan R. C., 1996, ApJ, 392, L9
Trnka D. et al., 2005, Phys. Rev. Lett., 94, 192303
Tsang M. B. et al., 2012, Phys. Rev. C, 86, 015803
Voskresensky D. N., 1997, Phys. Lett. B, 392, 262
Zschiesche D., Zeeb G., Paech K., Stoecker H., Schramm S., 2005, J. Phys. G, 30, S381

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