QCD in neutron stars and strange stars

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Abstract. This paper provides an overview of the possible role of Quantum Chromo Dynamics (QCD) for neutron stars and strange stars. The fundamental degrees of freedom of QCD are quarks, which may exist as unconfined (color superconducting) particles in the cores of neutron stars. There is also the theoretical possibility that a significantly large number of up, down, and strange quarks may settle down in a new state of matter known as strange quark matter, which, by hypothesis, could be more stable than even the most stable atomic nucleus, $^{56}$Fe. In the latter case new classes of self-bound, color superconducting objects, ranging from strange quark nuggets to strange quark stars, should exist. The properties of such objects will be reviewed along with the possible existence of deconfined quarks in neutron stars. Implications for observational astrophysics are pointed out.

Keywords: Quark matter, neutron stars, quark stars, nuclear equation of state

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INTRODUCTION

Astrophysicists distinguish between three types of compact stars. These are white dwarfs, neutron stars, and black holes. Of the three, neutron stars appear particularly interesting for QCD related studies of ultra-dense matter, since the matter in the cores of such objects is compressed to densities that are several times higher than the densities of atomic nuclei [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. Theoretical studies indicate that at such densities hyperons may be generated and new states of matter–such as boson condensates and/or quark matter–may appear [1, 2, 3, 6]. The latter ought to be a color superconductor [11, 12, 13]. There is also the intriguing theoretical possibility that strange quark matter could be more stable than even the most stable atomic nucleus [14], $^{56}$Fe, which would give rise to the existence of new classes of compact objects, carrying baryon numbers ranging from $\sim 10^2$ (quark nuggets) to $\sim 10^{57}$ (strange quark stars) [5, 15, 16, 17, 18, 19]. This paper summarizes the role of QCD for neutron stars and strange stars. Particular emphasis is put on the role of strangeness. Strangeness is carried by hyperons, quark matter, and quark nuggets, and may leave its mark in the masses, radii, cooling behavior, pycno-nuclear reactions, and the spin evolution of compact stars.

LIMITS ON THE CENTRAL DENSITIES OF NEUTRON STARS

Stringent limits on the central densities of neutron stars [20, 21] can be established through a variational study of the poorly known nuclear equation of state [1, 2, 3, 6, 8,
10]. Such a study assumes that the equation of state of neutron star matter is known up to an energy density $\varepsilon_0$ and pressure $p_0$, Einstein’s theory of general relativity is the correct theory of gravity, neutron star matter is microscopically stable (i.e., $\partial P/\partial \varepsilon > 0$), and that causality if not violated (i.e., $\partial P/\partial \varepsilon < 1$) [20, 22]. Models for the nuclear equation of state can then be generated from the following ansatz [22],

$$
\varepsilon(u) = \frac{\alpha}{\gamma - 1}(u^\gamma - u) + u\varepsilon_0 + (1 - u)(\alpha - p_0), \quad p(u) = \alpha(u^\gamma - 1) + p_0,
$$

(1)

where $p$ denotes pressure, $\varepsilon$ stands for the energy density, and $u \equiv \rho/\rho_0$ with $\rho$ the baryon number density. The quantities $\alpha$ and $\gamma$ are parameters that control the softness/stiffness of the nuclear equation of state. The result of such a study [23] show that the variational upper limit on the masses of neutron stars is close to $2.9 M_\odot$. Such stars could have central densities up to four times higher than the density of nuclear matter. Very recently the discovery of a very massive neutron star, PSR J1614-2230, was reported in [24]. This neutron star has a mass of $1.97 \pm 0.04 M_\odot$ and rotates at 3.15 milliseconds, which, however, has only very little impact on the star’s structure. According to the study presented above, the central density of this object could be anywhere between $2 \lesssim \varepsilon/\varepsilon_0 \lesssim 10$ [23], the high end of which evidently favoring the existence of exotic matter in the core of this object (for a general discussion, see [25, 26]).

**QUARK MATTER IN THE INNER CORES OF NEUTRON STARS**

It has been suggested already many decades ago [27, 28, 29, 30, 31, 32, 33] that the nucleons may melt under the enormous pressure that exists in the cores of neutron stars, creating a new state of matter known as quark matter. From simple geometrical considerations it follows that for a characteristic nucleon radius, $r_N$, of around one Fermi, nucleons may begin to touch each other in nuclear matter at densities $(4\pi r_N^3/3)^{-1} \simeq 0.24 \text{ fm}^{-3} = 1.5 \rho_0$, which is less than twice the number density of nuclear matter ($\rho_0 = 0.16 \text{ fm}^{-3}$). This value increases to $\sim 11 \rho_0$ for a nucleon radius of $r_N = 0.5 \text{ fm}$. One may thus speculate that the nucleons making up neutron star matter begin to dissolve at densities somewhere between around $2 - 10 \rho_0$, giving way to quark matter made up of unconfined up and down quarks. Depending on rotational frequency and neutron star mass, densities greater than two to three times $\rho_0$ may be easily reached in the cores of neutron stars so that the neutrons and protons in the cores of neutron stars may indeed be broken up into their quarks constituents [1, 2, 5, 34]. More than that, since the mass of the strange quark is only $m_s \sim 150 \text{ MeV}$, high-energetic up and down quarks will readily transform to strange quarks at about the same density at which up and down quark deconfinement sets in. Thus, if quark matter exists in the cores of neutron stars, it should be made of the three lightest quark flavors. Possible astrophysical signals of quark deconfinement in the cores of neutron stars were suggested in Refs. [35, 36, 37, 38, 39]. They all have their origin in the changes of the moment of inertia caused by the gradual transformation of hadronic matter into quark matter, which may lead to braking indices vastly different from the canonical value of 3, to the spin-up of isolated rotating neutron stars for extended (millions of years) periods of time, and to the pile-up of the frequencies of (X-ray) neutron stars accreting matter from companion
stars. If quark matter exists in neutron stars, it will consist of the three lightest quark flavors only. Quarks carrying charm, top or bottom flavors are much too massive to be generated in neutron stars [2, 5].

PYCNONUCLEAR REACTIONS

The lattice structures of the crusts of neutron stars makes these regions suitable environments where pycnonuclear (fusion) reactions among atomic lattice nuclei may occur [40, 41]. Model calculations [42] indicate that the presence of strange quark matter nuggets could alter these pycnonuclear reaction rates among the atomic lattice nuclei tremendously, as shown in Fig. 1. The differences in the reaction rates have their origin in the different mass-to-charge ratios of strange quark matter nuggets and atomic nuclei. The calculations in Fig. 1 are based on the assumption that strange quark nuggets are made up of either ordinary strange quark matter (NCFL) or color superconducting strange quark matter whose condensation pattern is the color-flavor-locked (CFL) phase. One crucial difference between non-CFL (NCFL) and CFL quark matter is the equality of all quark Fermi momenta in CFL quark matter which leads to charge neutrality in bulk without any need for electrons [43]. This has most important consequences for the charge-to-mass ratios of strangelets. For ordinary (NCFL) strangelets, the charge is approximately $Z \approx 0.1 m_{150}^2 A$ for $A \ll 10^3$, and $Z \approx 8 m_{150}^2 A^{1/3}$ for $A \gg 10^3$, where $m_{150} \equiv m_s/150$ MeV and $m_s$ is the mass of the strange quark. For small $A$, the charge is the volume quark charge density multiplied by the strangelet volume with a result that is proportional to $A$ itself. This relation holds until the system grows larger than around 5 fm, or $A \approx 150$, at which point the charge is mainly distributed near the strangelet surface, and $Z \propto A^{1/3}$ [44]. In contrast to this, the charge-to-mass ratio of CFL strangelets is described by $Z \approx 0.3 m_{150} A^{2/3}$ [44] which leads to a significantly increased pycnonuclear reaction rates in the crusts of neutron stars, as shown in Fig. 1. Possible observational consequences concern the thermal evolution of neutron stars [45, 46] and maybe superbursts [47, 48, 49].
ULTRA-HIGH ELECTRIC FIELDS AND VORTEX EXPULSION

We now turn our attention to strange quark matter objects at the high baryon number end \((A \sim 10^{57})\), also known as strange quark stars. If existing, these objects would have masses and radii that are similar to those of neutron stars, which makes it hard to distinguish both types of stars from one another observationally. One of the major differences between neutron stars and strange stars is that the latter are self-bound objects so that very light but small (radii on the order of just a few kilometers) strange quark stars could fill the Universe. Another striking feature of strange quark stars concerns the existence of ultra-high electric fields at their surfaces [50, 51, 52, 53]. This electric field is a consequence of a high electron concentration near the stellar surface, which is necessary to compensate the lower strange quark population in this region, and to maintain electric charge neutrality. As shown in [50, 51, 52, 53], these electrons are screened out of the star and form an electric dipole layer with an electric field on the order of \(E \sim 10^{17} - 10^{19}\) \(\text{V/cm}\). Electric fields of this magnitude can increase the stellar mass by up to 15\% [54]. This is an important result since it allows for the interpretation of massive pulsars as rotating strange stars.

The surface electric field can also give rise to differential rotation of the star with respect to its surrounding electric surface field [55]. In this event electric currents are generated at the surface of the strange star. The strength of these currents is determined by the magnitude of the net electric charge and by the amount of differential rotation. The magnetic field of such a configuration was found to be uniform inside the star, and of a dipole type outside [55]. Moreover, depending on the electric field and the relative frequency between the star and the electron layer, the generated magnetic fields may be as high as \(10^{16}\) \(\text{G}\). Such strong fields can be achieved for very high static electric fields on the order of \(\sim 10^{20} - 10^{21}\) \(\text{V/cm}\) and effective frequencies of \(\sim 700 - 1000\) \(\text{Hz}\). For small effective rotational frequencies of \(\sim 10\) \(\text{Hz}\) and more moderate static electric fields of \(\sim 10^{16} - 10^{18}\) \(\text{V/cm}\) one obtains magnetic fields on the order of \(10^9 - 10^{11}\) \(\text{G}\). This is a very intriguing result because such magnetic fields and rotational frequencies are in good agreement with the observed magnetic fields and frequencies of three Central Compact Objects (CCOs) [55]. CCOs form a group of recently discovered compact stars that are characterized by a faint steady flux predominately in the X-ray range and the absence of optical and radio counterparts [56, 57]. CCOs have relatively long rotational periods and, for the three cases for which data exists, possess small magnetic fields of \(\sim 10^{11}\) \(\text{G}\) [57]. These objects could thus be comfortably interpreted as rotating strange stars whose electron atmospheres rotate at frequencies that a slightly different from the ones of the stellar cores. The scenario described just above is only for strange stars made of color-flavor locked (CFL) superconducting quark matter but not for two-flavor color superconducting (2SC) quark matter, which has very different properties [13].

Strange stars made of CFL quark matter ought to be threaded with rotational vortex lines within which the star’s interior magnetic field is confined. If so, the vortices (and thus magnetic flux) would be expelled from the star during stellar spin-down, leading to magnetic reconnection at the surface of the star and the prolific production of thermal energy [58]. In [59] it was shown that this energy release can re-heat quark stars to exceptionally high temperatures, such as observed for Soft Gamma Repeaters (SGRs), Anomalous X-Ray pulsars (AXPs), and X-ray dim isolated neutron stars (XDINs).
Moreover, numerical investigations [59] of the temperature evolution, spin-down rate, and magnetic field behavior of such superconducting quark stars suggest that SGRs, AXPs, and XDINs may be linked ancestrally. Finally, the density at which quarks deconfine follows from this study to be of the order of five times that of nuclear saturation density, which is well within reach of typical neutron star densities [1, 2, 3, 4, 6, 7, 8, 9, 10].

CONCLUSIONS

The purpose of this short paper is to provide an overview of the multifaceted role of QCD for compact stars. We began with an investigation of the maximum densities of neutron stars. The results indicate that even very massive (∼2M⊙) neutron stars can have tremendous central densities (up to 10 time nuclear), which leaves plenty of leeway for the possible existence of hyperons, boson condensates, and/or deconfined up, down and strange quarks in the cores of such objects. Depending on the details of a possible deconfinement phase transition in the cores of neutron stars, anomalies in the rotational evolution (backbending) may be triggered by the transition which could be observed by radio and X-ray telescopes. If strange quark matter were absolutely stable, nuggets made of strange quark matter could exit in the crusts of neutron stars. If in the CFL phase, the presence of such nuggets may tremendously increase the pycnonuclear reaction rates in the crusts of neutron stars, which may serve as an observational window on the actual existence of strange quark matter. Stars made of strange quark matter could possess huge electric fields, increasing the stellar mass by up to 15%. This is an important result since it facilitates the interpretation of massive pulsars as rotating strange quark stars. Finally it was pointed out that CFL superconducting strange stars may distinguish themselves from ordinary neutron stars by differentially rotating electron surface layers, which could explain the magnetic fields observed for several compact central objects, and the possibility of vortex expulsion of magnetic flux lines from the star, which leads to a significant reheating of such stars. The computed temperatures are in excellent agreement with those observed for those of magnetars.

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REFERENCES

1. N. K. Glendenning, Compact Stars, Nuclear Physics, Particle Physics, and General Relativity, 2nd ed. (Springer-Verlag, New York, 2000).
2. F. Weber, Pulsars as Astrophysical Laboratories for Nuclear and Particle Physics, High Energy Physics, Cosmology and Gravitation Series (IOP Publishing, Bristol, Great Britain, 1999).
3. Physics of Neutron Star Interiors, ed. by D. Blaschke, N. K. Glendenning, and A. Sedrakian, Lecture Notes in Physics 578 (Spring-Verlag, Berlin, 2001).
4. M. Baldo and F. Burgio, Microscopic Theory of the Nuclear Equation of State and Neutron Star Structure, Lecture Notes in Physics 578, (Springer-Verlag, Berlin, 2001), p. 1.
5. F. Weber, Prog. Part. Nucl. Phys. 54 (2005) 193.
6. P. Haensel, A. Y. Potekhin, and D. G. Yakovlev, Neutron Stars 1, Astrophysics and Space Science Library, (Springer-Verlag, New York, 2006).
7. D. Page and S. Reddy, Ann. Rev. Nucl. Part. Sci. 56 (2006) 327.
8. T. Klähn et al., Phys. Rev. C 74 (2006) 035802.
9. A. Sedrakian, Prog. Part. Nucl. Phys. 58 (2007) 168.
10. T. Klähn et al., Phys. Lett. B 654 (2007) 170.
11. K. Rajagopal and F. Wilczek, The Condensed Matter Physics of QCD, At the Frontier of Particle Physics/Handbook of QCD, ed. M. Shifman, (World Scientific, 2001).
12. M. Alford, Ann. Rev. Nucl. Part. Sci. 51 (2001) 131.
13. M. G. Alford, A. Schmitt, K. Rajagopal, and T. Schäfer, Rev. Mod. Phys. 80 (2008) 1455.
14. E. Witten, Phys. Rev. D 30 (1984) 272.
15. E. Farhi and R. L. Jaffe, Phys. Rev. D 30 (1984) 2379.
16. J. Schaffner-Bielich, C. Greiner, A. Diener, and H. Stöcker, Phys. Rev. C 55 (1997) 3038.
17. J. Madsen, Phys. Rev. Lett. 81 (1998) 3311.
18. I. Sagert, M. Wietoska, J. Schaffner-Bielich, J. Phys. G 32 (2006) S241.
19. M. Alford, K. Rajagopal, S. Reddy, and A. W. Steiner, Phys. Rev. D 73 (2006) 114016.
20. J. B. Hartle, Phys. Rep. 46 (1978) 201.
21. J. Lattimer and M. Prakash, Phys. Rev. Lett. 94 (2005) 111101.
22. N. K. Glendenning, Phys. Rev. D 46 (1992) 1416.
23. F. Weber, O. Hamil, K. Mimura, and R. Negreiros, IJMP 19 (2010) 1427.
24. P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts and J. W. T. Hessels, Nature 467 (2010) 1081.
25. M. Coleman Miller, Nature 467 (2010) 1057.
26. F. Özel, D. Psaltis, S. Ransom, P. Demorest, and M. Alford, Astrophys. J. 724 (2010) L199.
27. D. D. Ivanenko and D. F. Kurdgelaidze, Astrophys. 1 (1965) 251.
28. H. Fritschw, M. Gell–Mann, and H. Leutwyler, Phys. Lett. 47B (1973) 365.
29. G. Baym and S. Chin, Phys. Lett. 62B (1976) 241.
30. B. D. Keister and L. S. Kisslinger, Phys. Lett. 64B (1976) 117.
31. G. Chapline and M. Nauenberg, Phys. Rev. D 16 (1977) 450.
32. W. B. Fechner and P. C. Joss, Nature 274 (1978) 347.
33. G. Chapline and M. Nauenberg, Ann. New York Academy of Sci. 302 (1977) 191.
34. N. K. Glendenning, Phys. Rev. D 46 (1992) 1274.
35. N. K. Glendenning, S. Pei, and F. Weber, Phys. Rev. Lett. 79 (1997) 1603.
36. N. K. Glendenning and F. Weber, Signal of Quark Deconfinement in Millisecond Pulsars and Reconfinement in Accreting X-ray Neutron Stars, Lecture Notes in Physics 578, (Springer-Verlag, Berlin, 2001), p. 305.
37. N. K. Glendenning and F. Weber, Astrophys. J. 559 (2001) L119.
38. E. Chubarian, H. Grigorian, G. Poghosyan, and D. Blaschke, Astron. & Astrophys. 357 (2000) 968.
39. N. K. Glendenning and F. Weber, Spin Clustering as Possible Evidence of Quark Matter in Accreting X-ray Neutron Stars, AIP conf. proc. 610 (2002) p. 470.
40. L. R. Gasques, A. V. Afanasjev, E. F. Aguilera, M. Beard, L. C. Chamon, P. Ring, M. Wiescher, and D. G. Yakovlev, Phys. Rev. C 72 (2005) 025806.
41. D. G. Yakovlev, L. R. Gasques, M. Beard, M. Wiescher, and A. V. Afanasjev, Phys. Rev. C 74 (2006) 035803.
42. B. Golf, J. Hellmers, and F. Weber, Phys. Rev. C 80 (2009) 015804.
43. K. Rajagopal and F. Wilczek, Phys. Rev. Lett. 86 (2001) 3492.
44. J. Madsen, Phys. Rev. Lett. 87 (2001) 172003.
45. D. Page, U. Geppert, and F. Weber, Nucl. Phys. A 777 (2006) 492.
46. M. Stejner, F. Weber, and J. Madsen, Astrophys. J. 694 (2009) 1619.
47. D. Page and A. Cumming, Astrophys. J. 635 (2005) L157.
48. M. Stejner and J. Madsen, Astron. Astrophys. 458 (2006) 523.
49. R. L. Cooper, A. W. Steiner, and E. F. Brown, Astrophys. J. 702 (2009) 660.
50. C. Alcock, E. Farhi, and A. V. Olinto, Astrophys. J. 310 (1986) 261.
51. C. Alcock and A. V. Olinto, Ann. Rev. Nucl. Part. Sci. 38 (1988) 161.
52. V. V. Usov, Phys. Rev. D 70 (2004) 067301.
53. V. V. Usov, T. Harko, and K. S. Cheng, Astrophys. J. 620 (2005) 915.
54. R. Negreiros, F. Weber, M. Malheiro, and V. Usov, Phys. Rev. D 80 (2009) 083006.
55. R. P. Negreiros, I. N. Mishustin, S. Schramm, and F. Weber, PRD 82 (2010) 103010.
56. W. Becker, and J. Truemper, ASSL 357 (2009) 91.
57. J. P. Halpern and E. V. Gotthelf, Astrophys. J. 709 (2010) 436.
58. R. Ouyed, Ø. Elgarsøy, H. Dahle, and P. Keränen, Astron. & Astrophys. 420 (2004) 1025.
59. B. Niebergal, R. Ouyed, R. Negreiros, and F. Weber, PRD 81 (2010) 043005.