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QUARK MATTER AT THE INTERIOR OF NEUTRON STARS

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Abstract. The density at the center of a neutron star reaches several times nuclear matter saturation density. At this density, the properties of strongly interacting matter are not well known. Exotic phases, such as hyperon matter, can appear. It is even possible that there is a phase transition to deconfined quark matter. Recent studies suggest that the phase structure of QCD in this domain is very rich. I will present the main characteristics of quark matter at high density as well as some observable consequences.

1 Introduction

The structure of the QCD phase diagram is one of the most exciting topics in the field of strong interactions (for reviews see, e.g., Alford et al. 2007). For a long time the discussion was restricted to two phases: the hadronic phase and the quark-gluon plasma (QGP). The former contains "our" world, where quarks and gluons are confined to color-neutral hadrons, whereas in the QGP quarks and gluons are deconfined.

At large enough density, nuclear matter is expected to undergo a phase transition to the deconfined phase, where quarks and gluons are free to move in the medium. Unfortunately, this transition is not well understood, since QCD lattice calculations cannot yet be performed at large density, i.e., at large chemical potential. Experimentally, in ultra-relativistic heavy ion collisions the transition to the deconfined phase is expected to occur at high temperature but essentially at zero baryon density. On the other hand, neutron stars are believed to contain very high baryon density in their interior, where the transition to the deconfined phase could occur. It has been argued by several authors that the properties of neutron stars can be strongly affected by the presence of a core where a quark phase or a mixed hadron-quark phase is present. The fact that the quark phase - if present - is likely to be a color superconductor has recently attracted much attention.

The intention of this talk will not be to discuss all the different possible color superconducting phases, but I will focus on some examples in order to discuss the main concepts of high density quark matter and the possible impact on neutron star phenomenology.

2 Color superconducting quark matter

Since QCD on the perturbative level provides an attractive interaction between quarks in certain channels, it is rather obvious to think of color superconducting phases in analogy with the Cooper mechanism for electrons responsible for the well-known electromagnetic superconductivity. Based on this idea, color superconducting phases were discussed already in the 70's (cf. for example Barrois 1977) and 80's (Bailin & Love 1984). But until quite recently not much attention was payed to this possibility. This changed dramatically after it was discovered that due to non-perturbative effects, the gaps which are related to these phases could be of the order of $\Delta \sim 100$ MeV (Alford et al. 1998; Rapp et al. 1998), much larger than expected from the early perturbative estimates. Since in standard weak-coupling BCS theory the critical temperature is given by $T_c \simeq 0.57\,\Delta(T=0)$, this also implies that T_c is much larger than the typical temperature of a neutron star older than some minutes. It was concluded that color superconducting phases could be relevant for compact stars (Weber 1999).

Rather soon after the beginning of this new era, it was noticed that there is probably more than one color superconducting phase in the QCD phase diagram. Due to the large number of quark degrees of freedom –color, flavor, and spin– there are many channels where diquark condensation is neither forbidden by Pauli principle

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nor by symmetries. Thus the interactions have to decide about the actual condensation pattern realized at a given density or a given chemical potential and temperature.

In order to describe quark matter at the interior of a compact star, it is important to consider electrically and color neutral matter in β-equilibrium. In addition to the quarks we also allow for the presence of leptons, especially electrons and muons. As we consider stars older than a few minutes, when neutrinos can freely leave the system, lepton number is not conserved.

At large density, for chemical potentials much larger than the strange quark mass, three-flavor pairing, i.e. including up-, down-, and strange quarks (CFL phase), is energetically favored. The neutrality conditions are in favor of the CFL phase at moderate densities, too, since in particular the condition for electrical neutrality induces a considerable mismatch between the Fermi-momenta of up- and down quarks and renders therefore a standard BCS-type two-flavor pairing (2SC phase) difficult. Unfortunately there is actually no means to treat the problem of quark matter at densities relevant for neutron stars from first principles. This means, that although the general ideas are clear, the details of the phase diagram depend on the exact interaction model chosen. In general, models where the quark masses are generated dynamically, like in NJL-type models (cf. Buballa 2005 for a review) allow for a two-flavor pairing window, whereas in Bag models only three-flavor phases exist even at moderate densities if neutrality is imposed (cf. for example Alford & Reddy 2003). Several other possibilities, such as crystalline phases, where the mismatch of Fermi-momenta is compensated by a nonzero momentum of the diquark condensate, or gapless phases, have been considered in the literature, too. In the two-flavor case, the remaining quarks can form “exotic” phases, like spin-1 condensates. For recent versions of the phase diagram of neutral color superconducting quark matter, see for example Ruester et al. (2005).

Concerning the value of the strange quark mass, let us mention the work by Nickel et al. (2006). They show that within a self-consistent Dyson-Schwinger approach, the screening of gluons at the relevant densities for neutron stars lowers the strange quark mass such that within this self-consistent treatment the CFL phase stays favored over two-flavor pairing all the way down to hadronic matter. The calculations are, however, very involved, such that this model has for the moment not been applied to neutron stars.

3 Compact stars with a color superconducting quark matter core

This section will be devoted to the study of the composition of a neutron star including the possibility of a quark matter core or even a pure quark star. In general, as already mentioned above, it is very difficult to establish on first principles the properties of quark matter at the relevant densities. In the literature mainly two types of models are used: Bag models and NJL-type models. For the phenomenology of neutron stars, the main difference is that within the latter the quark masses are generated dynamically and the strange quark mass is still rather high for densities at the interior of a neutron star. This leads to a gravitational instability within these models if strange quark states become populated (cf. Baldo et al. 2003). That means, that in contrast to Bag model studies, only two-flavor quark matter can exist in hybrid stars and in particular, no pure quark stars exist within NJL type models because they require the existence of absolutely stable strange quark matter. And even the parameter window allowing for hybrid stars with two-flavor quark matter is in general rather small (cf. Buballa 2005).

One often studied observable is the mass-radius relation of a non-rotating star. This is interesting in the context of pure quarks stars, because they are self-bound objects and the mass-radius relation has therefore a very different behavior than for normal neutron stars. In particular, for very small masses and radii, it follows a $M \sim R^3$ curve and the resulting radii are smaller for a given mass than for neutron stars. This means that the discovery of an object with a small radius and a typical neutron stars mass would be a strong indication for a quark star. Another possibility is that recent QPO observations could exclude parts of the mass-radius diagram and be in favor of a quark star interpretation, too (cf. Boutelier, M. 2008).

For hybrid stars, the situation is less obvious. Due to the additional degrees of freedom, the EOS in general becomes softer if one includes a possible quark phase. This means that the maximal masses become smaller. The same phenomenon can be observed for purely hadronic stars but allowing for the presence of hyperons, i.e. baryons containing in contrast to nucleons at least one strange quark, in the denser part of the star. Since color superconducting quark matter has a lower energy than normal quark matter, the maximum mass is even further reduced if quark matter is color superconducting. This can be seen from Fig. 1, where the mass-radius relation for different compact star configurations obtained by integrating the TOV equation for static non-rotating objects is displayed (cf. Buballa et al. 2004). The dash-dotted line represents purely hadronic

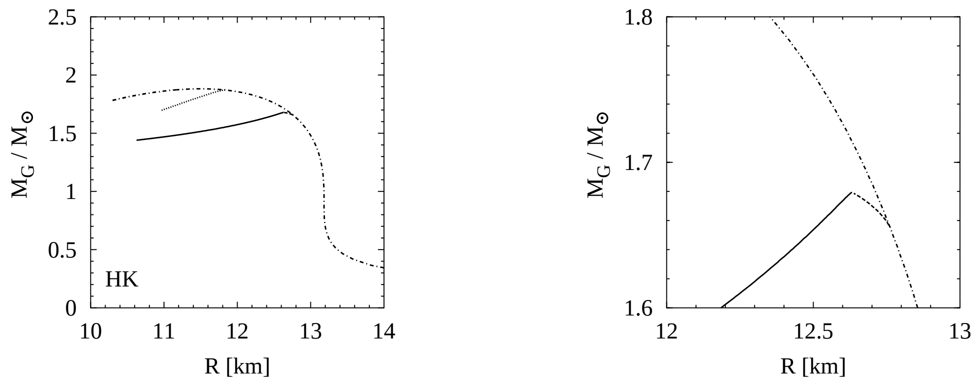

Fig. 1. Mass-radius relation of compact star configurations with a chiral $SU(3)$ model for the hadronic phase (Hanauske et al. 2000) and an NJL-type model for the quark phase including color superconductivity. The right panel shows the details of the phase transition region.

configurations, the dotted line configurations with a normal quark-matter core and the solid one configurations with color superconducting quark-matter cores in the 2SC and CFL phase. The phase transition part of the figure is again shown in more detail on the right hand side of Fig. 1. It can be seen that there is only a very small region, where stable hybrid stars exist. Note, however, that the star becomes unstable at the 2SC-CFL phase transition, such that we only find a hybrid star with a two-flavor quark core. The reason is, as explained above, the high strange quark mass in NJL-type models as applied here.

The existence of a hybrid star with a quark matter core can, however, not be ruled out if a high mass neutron star (typically with a mass above two solar masses) is observed, because the EOS of quark matter is not known well enough. A small repulsive vector interaction, for instance, could stiffen the quark matter EOS of state such that maximum masses above two solar masses can be accommodated (cf. Alford et al. 2005).

Many other possible signatures revealing the existence of a (color superconducting) quark matter core or even a pure quark star have been discussed. One interesting idea is based on the gravitational wave signal of neutron stars spiraling into black holes in binary systems (for a recent numerical simulation see Etienne et al. 2008). A step in the density profile at the interior of the neutron star resulting from a first order phase transition changes the form of the gravitational wave signal. Although the sensitivity of present detectors very probably is not sufficient, this could perhaps be detected in future gravitational wave detectors.

The above mentioned ideas are mainly based on the existence or not of a phase transition inside the neutron star. The superfluid or superconducting character of the matter only plays a minor role. There are, however, observables which are strongly influenced by superfluidity or superconductivity. First of all, let us mention the cooling behavior. The cooling of a neutron star is governed by neutrino emissivity and specific heat. The contribution to both quantities of particles paired in a scalar condensate (the dominant channel for almost all superfluid or superconducting phases inside a neutron star from the crust to a possible quark matter core) is suppressed exponentially at low temperatures as $\exp(-\Delta/T)$, where Δ is the energy gap in the spectrum and T the temperature. That means, quark matter in the CFL phase, where all quarks are paired, has a very low specific heat and neutrino emissivity. Unfortunately, this does not lead to any observable signal, since the cooling of the star is then dominated by the outer (hadronic) layers with higher specific heat and neutrino emissivity. The situation is different for two-flavor color superconducting phases, because there are quarks which remain unpaired or which pair in exotic condensates, such as spin-1, with much lower critical temperatures. This could give rise to rapid cooling due to direct Urca processes on unpaired quarks in early times before the temperature falls below the critical temperature for the "exotic" condensates. A more detailed discussion of the influence of two-flavor color superconducting phases on the cooling curves of neutron stars can be found in Popov et al. (2006).

The time of arrival of supernova neutrinos is another possible signal of a phase transition to CFL quark matter inside a neutron star. The most spectacular idea in this context is the following one: the neutrino mean free path is much longer in CFL matter than in all other phases inside a neutron star. A phase transition to CFL matter during the cooling down of the star could thus liberate all the previously trapped neutrinos and result in an increasing neutrino luminosity at the end of the supernova neutrino signal (Carter & Reddy 2000). It is, however, not clear whether this scenario survives a detailed simulation of supernova neutrino transport.

Another interesting field are the elastic properties such as r-mode instabilities. r-modes are oscillatory modes which transfer angular momentum from the star into gravitational radiation. At some critical spin frequency an instability exists which leads to an exponentially growing r-mode. In fact, the r-mode instability is very likely to impose the upper bound on observed spinning rates of pulsars since the mass-shedding limit is in general much higher than the observed frequencies. The damping of this instability is governed by viscosity. Here again, the contributions of gapped modes to the viscosity are damped exponentially. This means, the observation of millisecond pulsars with spin rates of several hundreds of Hz is inconsistent with a star formed uniquely of CFL quark matter because in that case the damping would be so low that the resulting maximum frequency is of the order of Hz or even below (cf. Madsen 2000).

In conclusion one should say that it is difficult to obtain information on the composition of neutron star matter from the different observations, but there are many interesting ideas for possible improvements in the (near) future.

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