ρ^- condensation in magnetised neutron stars

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The study of strongly interacting matter at high densities is one of the central themes of modern nuclear physics. Such a state of matter can be studied through the observations of neutron stars. It is expected that at high density the spontaneously broken chiral symmetry, characterized by a large quark condensate, is at least partially restored. Brown and Rho [1] suggested that hadrons experience a mass reduction in nuclear matter, which is proportional to the in-medium quark condensate. Calculations, using QCD sum rules and quark-meson models, also suggest such mass reduction. Direct evidence of mass reduction of vector mesons has been partially confirmed through the observation of the enhanced dilepton production [2].

On the other hand, QCD exhibits exciting physics in a strong magnetic field, since quarks are electrically charged and can be strongly affected by the field [3]. The magnetic field which typically can influence QCD effects is about $\sim 3 \times 10^{18}$ G. For the quark-antiquark bound state with light quarks, like ρ^- meson, strong magnetic fields can induce the formation of a condensate. 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 [3, 4]. In a highly dense matter onset of such condensation is further favoured. These extreme conditions can occur naturally in neutron stars (NS), where the density is several times the nuclear saturation density (n_0) and the magnetic field can be as high as $10^{18}-10^{19}$ G [5]. The high density would reduce the ρ^- mass due to in-medium effects and with the aid of strong magnetic field, a condensate could subsequently form.

We use a standard relativistic mean field (RMF) model, namely GM3, to study the possibility of ρ^- condensation. Here, for simplicity we adopt a linear dependence of the ρ^- mass on the scalar field

$$m^*_{\rho^-} = m_{\rho^-} - g\sigma \qquad (1)$$

where g is a dimensionless constant and m_{ρ^-} is the vacuum mass of the ρ^- meson. This term effectively introduces a coupling between the vector and scalar fields. On the other hand the magnetic field induces a change in ρ^- mass as

$$m^{*2}_{\rho^-} = m^2_{\rho^-} - eB. \qquad (2)$$

So, in principle, if the in-medium effect or magnetic field is high enough, the effective mass of the ρ^- meson can fall below the electron chemical potential (μ_e) so that electrons can be replaced by ρ^- mesons. In this case, we obtain a neutron star with ρ^- meson condensation. We solve the mean field equations at finite density including the additional term Eq. (1) and adjust g along with other parameters to guarantee that all the observable properties of nuclear matter are well reproduced.

The results for matter calculations are shown in Fig 1. In the upper panel of Fig. 1 the solid lines are for $g = 0$ and $B = 0$. In this case the ρ^- meson does not condense. The inclusion of the magnetic field ($B \sim 7.1 \times 10^{18}$ G) shifts the curves but is still not able to generate condensation (dashed lines). So, the magnetic field alone cannot give rise to condensation in a compact star. To produce ρ^- condensation solely due to magnetic field one needs $B \sim 3 - 4 \times 10^{19}$ G which is impossible to realise in a NS. For the condensation to take place, the ρ^- mass modification due to in-medium effect must be included. Taking this

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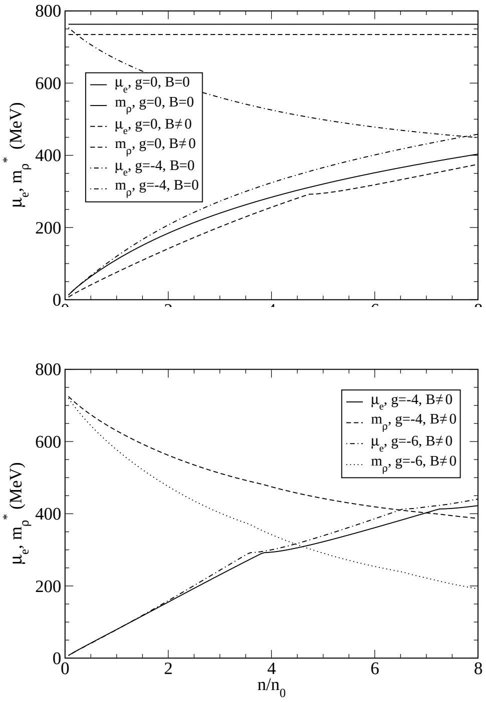

FIG. 1: μ_e (lower curves) and m_{ρ^-} (upper curves) are plotted as functions of normalized density.

effect, solely, into account we find that (dot-dashed lines) the condensation takes place at about $7.6n_0$ with $B = 0$ and $g = -4$. Recent observations suggest that the central energy density of NSs might lie around $5-6n_0$ [6]. In order for condensation to occur at such densities one must consider the effects of density-dependence of the mass and the effect of magnetic fields simultaneously. In lower panel of Fig 1. we plot curves for the case in which both effects are taken into account. With the above mentioned values of B and g the condensate sets in at approximately $6.9n_0$. However, if we now increase the value of g the condensate sets in at around $4.4n_0$. Therefore, for a neutron star with a central density of $6n_0$, a ρ^- meson condensate appears in the core of the star and extends up to the radius where the density is $4.4n_0$.

In Fig. 2, we plot the sequence of stars. The solid line represents the results where there is no ρ^- condensate. The dashed and dot-dashed curves are with ρ^- meson condensation. The dotted parts of these two curves indicate stars which have some amount of ρ^- condensate in their cores. As we increase g, the condensate appears much earlier i.e. more and more stars have a condensate region in their cores.

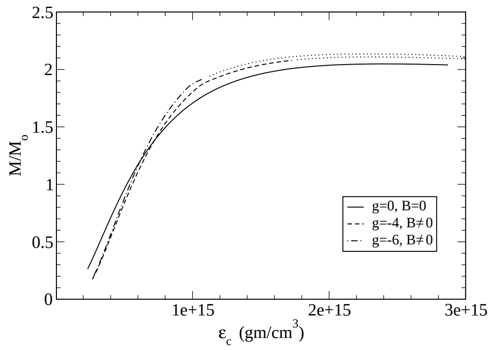

FIG. 2: Sequence of stars. The dotted lines indicate stars containing ρ^- condensate.

To summarise, we studied the possibility of ρ^- meson condensation within a RMF model. We have shown that such a state can be achieved, in a stellar environment, using quite reasonable parameters.

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