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ON THE EQUATION OF STATE IN EFFECTIVE QUARK THEORIES *

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We discuss the saturation mechanism for the nuclear matter equation of state in a chiral effective quark theory. The importance of the scalar polarizability of the nucleon is emphasized. The phase transition to color superconducting quark matter is also discussed.

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In order to discuss the question whether chiral symmetry is partially restored in the nuclear medium or not, one needs an equation of state (EOS) which is based on quark degrees of freedom and describes the nuclear saturation properties. This approach, which is sometimes called quark nuclear physics, forms a basis to describe not only normal nuclear systems, but also their interactions with high energy probes (DIS) and the transition to quark matter at high densities.

It is well known that the simple linear sigma model for point nucleons fails to describe the nuclear saturation. The reason for this failure is the rapid decrease of the sigma meson mass as a function of density. In the framework of a mean field description of nuclear systems, it can be shown very generally that the only place where the quark substructure of the nucleon comes into play is the scalar

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polarizability of the nucleon: Because of the polarization of the nucleon in the self consistent scalar nuclear mean field (σ), its mass $M_N(\sigma)$ develops a curvature ($\partial^2 M_N/\partial\sigma^2 > 0$) which is absent for point nucleons. This effect, which corresponds to a repulsive effective $\sigma\sigma NN$ interaction, stabilizes the nuclear matter against the chiral collapse[1]. In order to obtain a sufficiently large scalar polarizability in effective chiral quark models, it is necessary to eliminate unphysical quark decay thresholds for the nucleon, that is, to include the effect of the confinement.

The dramatic effects of the scalar polarizability and confinement are demonstrated in Fig.1, which shows the binding energy per nucleon in isospin symmetric nuclear matter, calculated in the framework of the Nambu-Jona-Lasinio (NJL) model. The scalar polarizability prevents the sigma meson mass to decrease too fast as a function of density, thereby putting limits on the attraction between the nucleons arising from sigma meson exchange. This can be seen in Fig.2, which shows that the Landau-Migdal parameter f_0 (scattering length in the medium) is attractive for small and normal densities but becomes repulsive at large densities, if the effect of the confinement is included. The results shown in Fig.2 correspond to a sigma meson mass which is only slightly reduced in the medium.

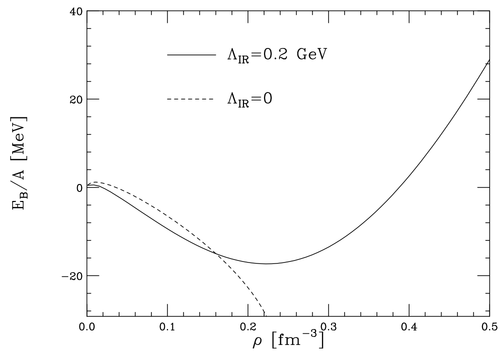

Fig. 1. Binding energy per nucleon as function of baryon density for the cases (i) finite infrared cut-off in the proper time regularization (quark decay thresholds are eliminated): solid line; and (ii) zero infrared cut-off (quark decay thresholds are present): dashed line.

Another interesting way of looking at the chiral behavior of nuclear matter is provided by the pion-nucleon sigma terms [a], which we define here as follows[1]:

$$\Sigma_{\pi N} = m\frac{\mathrm{d}\epsilon_F}{\mathrm{d}m}\,, \qquad \Sigma_{\pi NN} = m\frac{\mathrm{d}f_0}{\mathrm{d}m}\,. \tag{1}$$

Here m is the current quark mass, ϵ_F the nucleon Fermi energy, and f_0 the Landau-Migdal parameter discussed above. These 1-body and 2-body sigma terms are shown

[a]These sigma terms appear naturally in the expansion of the chiral condensate around any density, as the coefficients of the linear and quadratic terms. For zero density, $\Sigma_{\pi N}$ becomes the usual πN sigma term, while $\Sigma_{\pi NN}$ may have interesting relations to low energy pion-deuteron scattering.

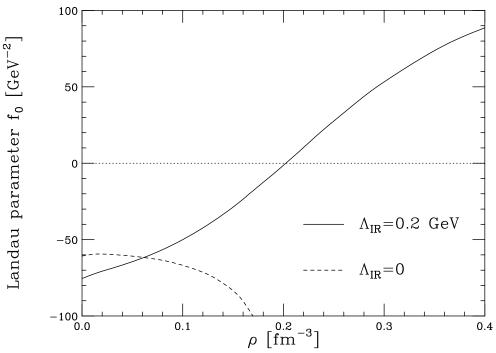

Fig. 2. Landau-Migdal parameter f_0 as function of baryon density for the two cases described in the caption of Fig.1.

as functions of the density in Fig.3. There are no spectacular changes in the chiral properties of the system as the density increases.

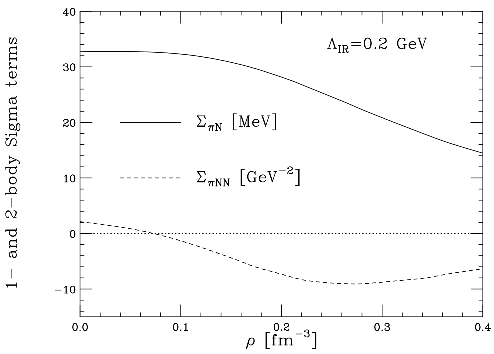

Fig. 3. 1-body and 2-body sigma terms defined in Eq.(1) as functions of the baryon density, for the case of finite infrared cut-off.

In order to discuss matter at high density, we construct also the quark matter EOS in the NJL model, including the possibility of color superconductivity, and use the Gibbs conditions to find transitions from the nuclear matter phase to the quark phase[2,3]. Some scenarios obtained for neutron star matter are shown in Figs. 4 and 5. The solid lines show the results for the pure nuclear matter EOS, the dashed lines for a phase transition to normal quark matter (no pairing in the quark phase), and the dotted lines for a phase transition to color superconducting quark matter (rather strong pairing in the quark phase). It is clear that the EOS becomes considerably softer for the latter case, and this strongly affects the neutron star masses.

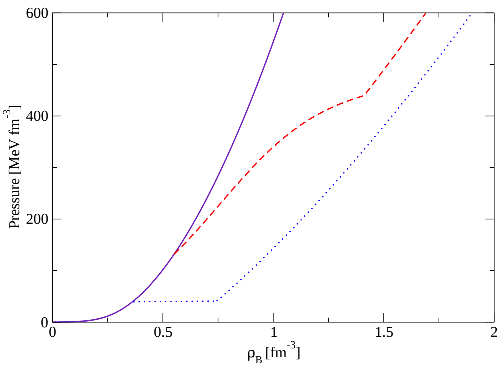

Fig. 4. Pressure of neutron star matter as function of baryon density: Pure nuclear matter (upper line), transition to normal quark matter (middle line), and transition to color superconducting quark matter (lower line).

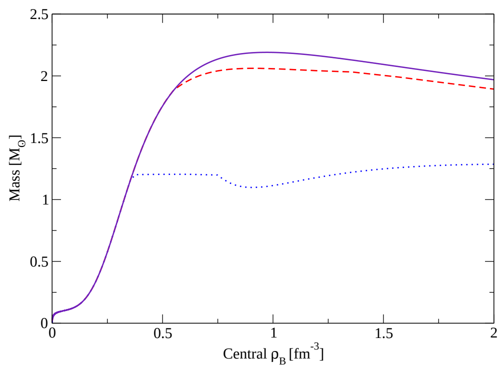

Fig. 5. Neutron star mass as function of the central baryon density for the 3 cases described in the caption of Fig.4.

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