Suppression of the repulsive force in nuclear interactions near the chiral phase transition

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Abstract: We introduce an effective chiral Lagrangian with a dilaton responsible for the trace anomaly in QCD. As the “dilaton limit” is taken, which drives a system to near chiral restoration density, a linear sigma model emerges from the highly non-linear structure. A striking prediction is that the vector-meson–nucleon interaction gets strongly suppressed when the dilaton limit is approached. Its phenomenological implications for the thermodynamics of dense baryonic matter are briefly discussed.

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1. Role of the dilaton at high density

In the limit of massless quarks the QCD Lagrangian possesses the chiral symmetry and scale invariance, both of which are dynamically broken in the physical vacuum due to the strong interaction. The QCD trace anomaly signals the emergence of a scale at the quantum level from the theory without any dimension-full parameters. Therefore, spontaneous chiral symmetry breaking, which gives rise to a nucleon mass, and the trace anomaly have an intimate connection to each other and dynamical scales in hadronic systems are considered to originate from them. In nuclear physics, a scalar meson plays an essential role as known from Walecka model that works fairly well for phenomena near nuclear matter density [1]. On the other hand, at high density, the relevant Lagrangian possessing correct symmetry is the linear sigma model, and the scalar needed there is the fourth component of the chiral four-vector ($\vec{\pi}, \sigma$). Thus in order to probe highly dense matter, we have to resolve how the chiral scalar at low density transmutes to the fourth component of the four-vector.

The trace anomaly is implemented in a chiral Lagrangian by introducing a dilaton (or glueball) field representing the gluon condensate $\langle G_{\mu\nu}G^{\mu\nu} \rangle$ [2]. Following [3], we express the trace anomaly in terms of “soft” $\chi_s$ and “hard”
χh dilatons. We associate the soft dilaton with that component locked to the quark condensate \( \langle \bar{q}q \rangle \) [4]. This is assumed to be the component which "melts" across the chiral phase transition whereas the hard one remains non-vanishing. The soft dilaton plays an important role in the emergence of a half-skyrmion phase at high density where a skyrmion turns into two half-skyrmions [5].

In introducing baryons, there are two alternative ways of assigning chirality to the nucleons, “naive” and mirror assignments. The “naive” assignment is anchored on the standard chiral symmetry structure where the entire constituent quark or nucleon mass (in the chiral limit) is generated by spontaneous symmetry breaking. The alternative, mirror assignment [6, 7] allows a chiral invariant mass term which remains non-zero at chiral restoration. Therefore a part of the nucleon mass, \( m_0 \), must arise from a mechanism that is not associated with spontaneous chiral symmetry breaking. The origin of such a mass \( m_0 \) can be traced back to the non-vanishing gluon condensate in chiral symmetric phase and the broken scale symmetry is accounted for by the hard dilaton. In this way the origin of \( m_0 \) is attributed to the hard component of the gluon condensate [8].

2. Dilaton limit

Our effective Lagrangian for the Nambu-Goldstone bosons, vector mesons and soft dilatons is derived [8] starting with the hidden local symmetric (HLS) [9] Lagrangian following the strategy of Beane and van Kolck [10]. Conformal invariance can be embedded in chiral Lagrangians by introducing a scalar field \( \tilde{\chi} \) via \( \chi = F \chi \tilde{\chi} \) and \( \kappa = (F_\pi / F_\chi)^2 \). Near chiral symmetry restoration the quarkonium component of the dilaton field becomes a scalar mode which forms with pions an O(4) quartet [10]. This can be formulated by making a transformation of a non-linear chiral Lagrangian to a linear basis exploiting the dilaton limit.

The linearized Lagrangian with nucleons in the “naive” assignment includes terms which generate singularities in chiral symmetric phase. Assuming that nature disallows any singularities, we require that they be absent in the Lagrangian. This leads to \( \kappa = 1 \) and the Yukawa couplings (nucleon axial and vector charges) \( g_A = g_V \). A special value, \( g_V = 1 \), is achieved as a fixed point of the renormalization group equations (RGEs) formulated in the chiral perturbation theory (ChPT) with HLS when one approaches chiral restoration from the low density or temperature side [11]. Thus, we adopt the dilaton limit as \( \kappa = g_A = g_V = 1 \). In fact \( g_V = g_A = 1 \) recovers the large \( N_c \) algebraic sum rules shown in [10].

A noteworthy feature of the dilaton-limit Lagrangian is that the vector mesons decouple from the nucleons while the pion-nucleon coupling remains. This has two striking new predictions. Taking the dilaton limit drives the Yukawa interaction to vanish as \( g_{VN}^2 = (g (1 - g_V))^2 \rightarrow 0 \) for \( V = \rho, \omega \) for any finite value of the HLS gauge coupling \( g \). In nuclear forces, what is effective is the ratio \( g_{VN}^2 / m_V^2 \) which goes as \( (1 - g_V)^2 \). This means that (1) the two-body repulsion which holds two nucleons apart at short distance will be suppressed in dense medium and (2) the symmetry energy \( S_{\text{sym}} \propto g_{VN}^2 \) will also get suppressed. Consequently, the EoS at some high density approaching the dilaton limit will become softer even without any exotic happenings such as kaon condensation.
or strange quark matter. An interesting possibility is that our mechanism could accommodate an exotica-free nucleon-only EoS (e.g. AP4 in Fig. 3 of Ref. [12]) with a requisite softening at higher density that could be compatible with the $1.97 \pm 0.04 \, M_\odot$ neutron star data [13].

In the present scheme, the shortest-range component of the three-body forces also vanishes in the dilaton limit. The one-pion exchange three-body force involving a contact two-body force will also get suppressed as $\sim g_{\omega N}^2$. Thus only the longest-range two-pion exchange three-body forces will remain operative at large density in compact stars. How this intricate mechanism affects the EoS at high density is a challenging issue to resolve.

The dilaton limit is unchanged by the mirror baryons and therefore similar phenomenological consequences are expected. Furthermore, the ChPT with either chirality assignment yields the dilaton limit as an infrared fixed point of the coupled RGEs [11]. This could be protected at quantum level by mended symmetry, which is the algebraic consequence of spontaneous broken chiral symmetry [14], and indeed becomes manifest when the dilaton limit sets in [8]. How large is $m_0$ at the chiral symmetry restoration? A rough estimate can be made from thermodynamic considerations and the gluon condensate calculated on a lattice in the presence of dynamical quarks [15]. It turns out to be $m_0 = 210 \, \text{MeV}$ and this is in agreement with the estimate made in vacuum phenomenology [11].

3. Conclusions and remarks

We have presented how an effective theory near chiral symmetry restoration emerges from the dilaton-implemented HLS Lagrangian, and discussed its phenomenological implications at high baryon density. The soft dilaton is responsible for the spontaneous breaking of the scale symmetry and its condensate vanishes when the chiral symmetry is restored. In fact, topological stability of the half-skyrmion phase has been observed [5]. This is a strong indication that the configuration is robust and it could be associated with the scale symmetry restoration at high density in continuum theories.

Our main observation on the suppressed repulsive interaction is a common feature in the two different assignments, “naive” and mirror, of chirality. The nucleon mass near chiral symmetry restoration exhibits a striking difference in the two scenarios. How the suppression of the repulsion at the dilaton limit – which seems to be universal independent of the assignments but may manifest itself differently in the two cases – will affect the EoS for compact stars is an interesting question to investigate.

In the scalar sector of low-mass hadrons, scalar quarkonium, tetra-quark states [16] and glueballs are all mixed. In a hot/dense medium the mixing depends on temperature and density and a multiple level-crossing among them will be expected. It is worth noting that using a toy model for constituent quarks and gluons implementing chiral and scale symmetry breaking a large sigma-meson mass $m_\sigma \sim 1 \, \text{GeV}$ in matter-free space is favored along with the lattice observation of the thermal gluon condensate [17], which is a conceivable scenario known from the phenomenology at zero temperature and density.
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