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Quark–meson coupling model with the cloudy bag

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ABSTRACT

Using the volume coupling version of the cloudy bag model, the quark–meson coupling model is extended to study the role of pion field and the properties of nuclear matter. The extended model includes the effect of gluon exchange as well as the pion-cloud effect, and provides a good description of the nuclear matter properties. The relationship between the extended model and the EFT approach to nuclear matter is also discussed.

The quark–meson coupling (QMC) model [1] can be considered as an extension of Quantum Hadrodynamics (QHD) to include the effect of the internal structure of a nucleon in matter. The model describes a nuclear system by non-overlapping MIT bags, in which the confined quarks interact through the self-consistent exchange of iso-scalar, scalar (σ) and vector (ω) mesons. In the past few decades, it has been extensively developed and applied to various nuclear phenomena with tremendous success [1].

On the other hand, a major breakthrough occurred in the problem of nucleon–nucleon (NN) force by introducing the concept of an effective field theory (EFT) [2]. The QCD Lagrangian for massless up and down quarks is chirally symmetric, and the axial symmetry is spontaneously broken. This implies the existence of the massless Nambu–Goldstone bosons, namely the pions. The non-zero pion mass is then a consequence of the fact that the light quark has a small mass. Thus, one arrives at a low-energy scenario that pions and nucleons (and possibly deltas) interact via a force governed by spontaneously broken, approximate chiral symmetry.

In EFT, the degrees of freedom of quarks and gluons (including heavy mesons and nucleon resonances) should be *integrated out* (or *cutoff*), because a probe with wavelength λ is insensitive to details of structure at distances much smaller than it [3]. Instead, it is necessary to add local (contact) interactions with low-energy constants (LECs) to the Lagrangian to mimic the effect of the true short distance physics. The LECs are determined empirically from fits to πN and/or NN scattering data, and vary with the momentum cutoff ($\sim \lambda^{-1}$) accounting for quantum fluctuations excluded by the cutoff [3]. Up to N^{3}LO, EFT can provide the peripheral NN scattering data (below about 250 MeV lab. energy) very accurately [4].

Recently, EFT has been intensively applied to the problem of nuclear matter. In addition to the usual (small momentum) expansion in the free NN or πN scattering, physical observables in matter are expanded in terms of the Fermi momentum k_F, which is also a relevant, small scale. Such density dependence arises from the Pauli blocking effect in matter, i.e., the medium insertion including the step-function, $\theta(k_F - |\vec{p}|)$, in the nucleon propagator. Then, the strengths of the LECs are fine-tuned so as to reproduce the nuclear matter properties [5].

If the internal structure of the nucleon were completely *frozen* in a nuclear medium or the same as that in free space, it might be sufficient to consider the density dependence solely stemming from the Pauli blocking effect. However, if the in-medium nucleon were metamorphosed depending on the nuclear density ρ_B, the situation may be different. In fact, the evidence for the medium modification of nucleon structure was observed in polarization transfer measurement in the quasi-elastic $(e, e'p)$ reaction at the Thomas Jefferson

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national accelerator facility, and the result supports the prediction of the QMC model [6]. It also seems vital to consider the internal structure change of the nucleon to understand the nuclear EMC effect [7].

The QMC model can describe the medium modification of the nucleon structure through the quark model, and predict the density (or mean scalar-field) dependence of physical quantities [1]. Expanding such modification in terms of k_F and comparing with the values of LECs given in the EFT approach,[1] it may be possible to study whether the internal structure change of a nucleon indeed shows up in matter, since the LECs involve all information on the short distance physics.

To carry out such a complicated investigation, as a first step, we need to develop a new version of the QMC model for nuclear matter, where the structure of nucleon (and delta) is treated based on chiral symmetry. We attempt this in the present study using the volume coupling version of the cloudy bag model (CBM), which incorporates major results of the current algebra for low energy πN scattering [9].

The Lagrangian density for the volume coupling version of the CBM in flavor SU(2) is given by [9]

$$\mathcal{L}_{\rm CBM}=\left[\bar\psi\left\{i\gamma_\mu\mathcal{D}^\mu+\frac{1}{2f_\pi}\gamma_\mu\gamma_5\vec\tau\cdot\left(D^\mu\vec\phi\right)\right\}\psi-B\right]\theta_V-\frac{1}{2}\bar\psi\psi\delta_S+\frac{1}{2}(D_\mu\vec\phi)^2+\mathcal{L}_{\chi B}, \tag{1}$$

with ψ the quark field, $\vec\phi$ the pion field, $\phi=(\vec\phi\cdot\vec\phi)^{1/2}$, $\hat\phi=\vec\phi/|\vec\phi|$, $f_\pi\,(=93$ MeV) the pion decay constant, B the bag constant, θ_V the step function for the bag, δ_S the surface δ-function, $D_\mu\vec\phi=(\partial_\mu\phi)\hat\phi+f_\pi\sin(\phi/f_\pi)\partial_\mu\hat\phi$ and $\mathcal{D}^\mu\psi=\partial^\mu\psi-\frac{i}{2}[\cos(\phi/f_\pi)-1]\vec\tau\cdot(\hat\phi\times\partial^\mu\hat\phi)\psi$. The last term includes the quark mass, m, which explicitly breaks chiral symmetry, and the pion mass, $m_\pi(=138$ MeV): $\mathcal{L}_{\chi B}=-m\bar\psi e^{-i\vec\tau\cdot\vec\phi\gamma_5/f_\pi}\psi\theta_V-\frac{1}{2}m_\pi^2\vec\phi^2$.

As in the CBM, we linearize the pion field and keep $\mathcal{O}(1/f_\pi)$ (the convergence properties of the CBM were given in Ref. [9]). The Lagrangian density then reads

$$\mathcal{L}_{\rm CBM}=\left[\bar\psi\left\{i\gamma_\mu\partial^\mu-m+i\frac{m}{f_\pi}\gamma_5\vec\tau\cdot\vec\phi+\frac{1}{2f_\pi}\gamma_\mu\gamma_5\vec\tau\cdot\left(\partial^\mu\vec\phi\right)\right\}\psi-B\right]\theta_V-\frac{1}{2}\bar\psi\psi\delta_S+\frac{1}{2}(\partial_\mu\vec\phi)^2-\frac{1}{2}m_\pi^2\vec\phi^2. \tag{2}$$

Here the pion field interacts with the quark through both the pseudovector (pv) and pseudoscalar (ps) couplings. The strength of the ps coupling is $\mathcal{O}(m/f_\pi)$, which explicitly shows the breaking scale of chiral symmetry.

We introduce the gluon field as well. The resulting Lagrangian density is thus given by

$$\mathcal{L}_{\rm CBM}=\mathcal{L}_{\rm BAG}+\mathcal{L}_\pi+\mathcal{L}_g+\mathcal{L}_{\rm int}, \tag{3}$$

where

$$\mathcal{L}_{\rm BAG}=\left[\bar\psi\left(i\gamma_\mu\partial^\mu-m\right)\psi-B\right]\theta_V-\frac{1}{2}\bar\psi\psi\delta_S, \tag{4}$$

$$\mathcal{L}_{\rm int}=\bar\psi\left[i\frac{m}{f_\pi}\gamma_5\vec\tau\cdot\vec\phi+\frac{1}{2f_\pi}\gamma_\mu\gamma_5\vec\tau\cdot\left(\partial^\mu\vec\phi\right)+\frac{g}{2}\gamma_\mu\vec\lambda\cdot\vec A^\mu\right]\psi\theta_V, \tag{5}$$

with $\vec\lambda$ the SU(3) generators and g the quark–gluon coupling constant. The free pion field and the kinetic energy of the gluon field, $\vec A^\mu$, are, respectively, described by $\mathcal{L}_\pi$ and $\mathcal{L}_g$.

We firstly calculate the second-order energy correction to the nucleon or delta mass. The energy shift of a multi-quark, ground state, $|0\rangle$, due to the interaction is given by the Hubbard's prescription

$$E-E_0=\langle 0|\sum_{m=1}^{\infty}(-i)^m\frac{1}{m!}\int i\delta(t_1)\,d^4x_1\cdots\int d^4x_m T\left[\mathcal{H}_{\rm int}(x_1)\cdots\mathcal{H}_{\rm int}(x_m)\right]|0\rangle_{\rm con.}, \tag{6}$$

where $\mathcal{H}_{\rm int}$ is the interaction Hamiltonian density. The energy shift is then given as $E^{(2)}=E_{\rm dr}+E_{\rm nd}$, where the first term is the direct contribution and the second one is the non-direct contribution. (See Eqs. (11) and (12) later.)

The noninteracting, quark green function is given by $iG^0(r,r')=\langle 0|T[\psi(r)\bar\psi(r')]|0\rangle$, and it can be separated into two pieces: $G^0(r,r')=\int\frac{d\omega}{2\pi}e^{-i\omega(t-t')}[G_F^0(\vec r,\vec r',\omega)+G_D^0(\vec r,\vec r',\omega)]$. The first term is the usual Feynman propagator in a spherical cavity (bag) and the second one describes the occupied, multi-quark ground state [10]

$$G_D^0(\vec r,\vec r',\omega)=\sum_{n\leqslant n_F}U_n(\vec r)\bar U_n(\vec r')2\pi i\delta(\omega-E_n), \tag{7}$$

where U_n is the positive energy state with a complete set of quark quantum numbers $n(=\{\nu\kappa\mu\mu_i\mu_c\})$ including isospin μ_i and color μ_c (n_F specifies the quantum numbers at the Fermi surface in a hadron).

Here we restrict the expansion of the quark propagator to the ground state, i.e., $\nu=0$ and $\kappa=-1$. Such a truncation may be considered as a regularization of the quark propagator, where in flavor SU(2) the intermediate baryon states in loop diagrams are restricted to the nucleon and delta [11]. This is consistent with the idea of the CBM. Thus, we let n label the spin, isospin and color $\{\mu\mu_i\mu_c\}$.

The pion propagator is defined by $i\Delta_{ab}(r,r')=\langle 0|T[\phi_a(r)\phi_b(r')]|0\rangle=i\delta_{ab}\Delta(r,r')$, where (a,b) specifies the isospin. It is then given by the multipole expansion

$$\Delta(r,r')=\sum_{\ell,m}\int\frac{d\omega}{2\pi}e^{-i\omega(t-t')}\Delta_\ell(r,r',\omega)Y_{\ell m}(\hat r)Y_{\ell m}^*(\hat r'). \tag{8}$$

The gluon propagator can be calculated in the Coulomb gauge[2]

[1] In fact, from the point of view of the quark and gluon degrees of freedom, the QMC model can explain the values of the coefficients appearing in the familiar (contact) Skyrme force in conventional nuclear physics [8].

[2] It can be shown that the result does not depend on the choice of the gauge [11].