QUARK MEAN FIELD MODEL FOR NUCLEUS

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It is very important to study the change of the nucleon properties in nuclei. There are several experimental indications on this change. The EMC effect is the most dramatic one, which indicates the swelling of the nucleon in nuclei, although other interpretations as the effects of binding energy and the pion cloud are not excluded [1]. The EMC effect also motivated many theoretical works on the study of hadrons in terms of quarks and gluons. Among them, the QCD sum rule suggests a large change of the masses of the vector mesons in nuclei. These possibilities are very important to pursue both theoretically and experimentally from various view points.

Guichon proposed an interesting model on the change of the nucleon properties in nuclear matter [2]. The model construction mimics the relativistic mean field theory, where the scalar and the vector meson fields couple not with nucleons but with quarks in nucleons. Hence, the nucleon properties change according to the strengths of the mean fields acting on the quarks. The nucleon is modeled in terms of the MIT bag model, where the quark mass is zero or close to zero in the free space and the interior region is in the perturbative vacuum separated with the non-perturbative vacuum by the bag. The scalar meson provides a strong attraction and as a consequence provides a negative mass to the quarks. The MIT bag model then reduces the nucleon mass in nuclear matter. This model has been extended by Thomas and his collaborators under the name of the quark-meson coupling (QMC) model and applied to many obervables [3].

The model relies strongly on the choice of the nucleon model, for which the QMC model uses the MIT bag model. Another popular model for the nucleon is the constituent quark model. In this model, quarks get masses due to the spontaneous chiral symmetry breaking. It is then very natural to have nearly zero mass pions and their coupling to the constituent quarks. This consideration makes a simple interpretation of the direct coupling of other mesons as σ and ω mesons.

We shall begin with a possible lagrangian of the quark many body system after taking into account the non-perturbative gluon dynamics of spontaneous chiral symmetry breaking and quark confinement. The effective lagrangian may be written as

$$\mathcal{L} = \bar{q}\,(i\gamma_\mu\partial^\mu - m_q - \chi_c - g\gamma_\mu A^\mu - g_i^q\phi_i\Gamma_i)\,q + \mathcal{L}(\text{Meson, Gluon})\,. \tag{1}$$

Here, q denotes the quark fields with constituent quark masses m_q, which is of the order of 300 MeV to be consistent with the quark condensate and the pion decay constant. The confinement is expressed in terms of χ_c, which is given by the gluon dynamics. The path from QCD to this expression is not settled yet. One promising method might be the use of the dual Ginzburg-Landau (DGL) theory, which contains QCD monopoles in the abelian space and their condensation to induce the dual Meissner effect [4]. A^μ are the gluon fields with the running coupling constant g at the model scale. On top, it is natural to have meson fields ϕ_i,

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which couple with quark fields with the Dirac matrices Γ_i and the coupling strength g_i^q. The rest $\mathcal{L}$(Meson, Gluon) denotes the boson dynamics, which is not specified here explicitely.

To proceed, we take the mean field approximation for the meson fields, of which the scalar and the vector mesons are most important and we restrict to σ and ω mesons at least in writing explicitely hereafter. The inclusion of other mesons is straight forward. If we know the way to work out the intrinsic system of the Dirac particles and derive the Dirac lagrangian for the composite system, we can go on straight forwardly with the above effective lagrangian. Since we do not know it, we work out the problem in two steps. First, we construct the nucleon with the meson mean fields $\sigma(r)$ and $\omega(r)$, which are provided by other nucleons. Then in the second step, we solve the entire nuclear system by knowing the individual nucleon properties due to the presence of the mean fields.

The first step is to generate the nucleon system under the influence of the meson mean fields. The quarks in a nucleon are given by the following Dirac equation,

$$\left(i\gamma_\mu\partial^\mu - m_q - \frac{1}{2}kr^2(1+\gamma^0)/2 - g_\sigma^q\sigma(r) - g_\omega^q\omega(r)\gamma^0\right) q(r) = 0, \tag{2}$$

in the rest frame of the nucleon. Here, we have written the confining potential in terms of the harmonic oscillator potential together with the special combination of gamma matrices for simplicity for the actual calculation. Assuming the meson mean fields are constant within the small nucleon volume, we can then write the Dirac equation in the more compact form

$$\left(-i\vec{\alpha}\cdot\vec{\nabla} + \frac{1}{2}kr^2(1+\beta)/2 + \beta m_q^*\right) q(r) = e^* q(r), \tag{3}$$

where $m_q^* = m_q + g_\sigma^q\sigma$ and $e^* = e - g_\omega^q\omega$, σ and ω being the mean fields at the middle of the nucleon. e is the energy of the quark under the influence of the σ and the ω mean fields. The quark mass is modified to m_q^* due to the presence of the sigma mean field. Here, the coupling constants g_σ^q and g_ω^q are the σ and ω quark coupling and they are related with the σ and ω nucleon coupling constants with some factor. We should take into account the spin correlations, E_{spin}, due to gluons and pions so that the mass difference between Δ and nucleon arises. There exists the spurious center of mass motion, which is removed in the standard method. We take the constituent quark mass to be one third of the nucleon mass; $m_q = M_n/3 = 313$ MeV.

We now move to the second step of constructing the nucleus with the change of the nucleon properties obtained in the first step. We need to calculate the meson mean fields. They are obtained by using the Euler-Lagrange (EL) equation for the meson fields with the use of the QMF lagrangian,

$$\mathcal{L}_{QMF} = \bar{\psi}\left(i\gamma_\mu\partial^\mu - M_n^*(\sigma) - g_\omega\omega\gamma^0\right)\psi + \mathcal{L}_M. \tag{4}$$

Here, ψ denotes the nucleon fields. The change of the nucleon properties has been worked out in the first step and the outcome is exclusively expressed in $M_n^*(\sigma)$. The ω quark coupling does not cause any change of the nucleon properties and it appears merely as the energy shift and this contribution is carried over here as the ω nucleon coupling term with the replacement of the coupling constant as $g_\omega = 3g_\omega^q$.

We calculate first the change of the nucleon properties as a function of the σ mean field. Due to the use of the special form for the confining potential, we can work out the Dirac equation analytically. We choose $k = 1000$ MeV/fm^2 for the strength of the confining

potential. We take a large mass range for modification of the quark mass in the medium. The single particle zero point energy varies from about 410-470 MeV to be canceled out with the center of mass energy and the spin correlation energy. We find interesting results on the effective nucleon mass M_n^* as a function of the mass correction, δm_q, which is defined as $\delta m_q = -g_\sigma^q \sigma$. The curve is almost a straight line and can be approximated as $M_n^* = M_n - 3\delta m_q \times 0.814$. This means that the derivative of the effective mass with respect to σ is constant. This is an amazing result. It means if we define the effective σ nucleon coupling as $g_\sigma = 3g_\sigma^q \times 0.814$ then the mean field equation for the σ becomes that of the standard mean field theory with the use of g_σ. Hence, all the results obtained for the nuclear properties in the relativistic mean field (RMF) theory are unchanged. However, the nucleon structure changes as the mass of the quarks, the size of the nucleon and hence many observables. Even if the nucleon properties change appreciably, the effective σ nucleon coupling remains unchanged and therefore the resuts of RMF and even the RBHF do not change.

We now make the nuclear matter calculation. We take the TM1 parameter set, which reproduces very nicely the nuclear ground state properties and also the results of the relativistic Brueckner-Hartree-Fock calculations [5]. We get the energy per particle as a function of the nuclear matter density and also the nucleon effective mass. Now the important thing to note is that the change of the nucleon mass is directly related with the change of the quark mass, δm_q, inside the nucleon. The amount of the quark mass change is about 145 MeV at the normal matter density. The nucleon size increases by about 7% at the normal matter density. It would be very interesting to calculate the EMC effect with the change of the nucleon properties, in particular, with the increase of the nucleon radius [3]. If we make a comparison with the QMC model here, a large reduction of the effective nucleon mass in nuclear matter in the present model provides the large spin-orbit splitting as required for finite nuclei, while only a small mass reduction is found in the QMC model [3].

We have developed the quark mean field (QMF) model to describe the change of nucleon properties in nuclei and at the same time the change of nuclear properties. We have used the constituent quark model for the nucleon, which naturally allows the direct coupling of sigma and omega mesons with quarks. The mean field lagrangian at the nucleon level reflects the direct coupling of mesons with quarks merely through the appearence of the effective nucleon mass, which is a function of the sigma mean field. With our model setting and our assumptions of the parameter choices, we have found that the effective mass changes almost linearly with the sigma mean field (quark mass correction). Hence, by defining the sigma nucleon coupling as $g_\sigma = 3g_\sigma^q \times 0.814$, we are able to use the results of all the hitherto obtained relativistic mean field (RMF) calculations.

References

[1] EMC, J.J. Aubert et al., Phys. Lett. **123B** (1983) 275.

[2] P. Guichon, Phys. Lett. **B200** (1988) 235.

[3] K. Saito, A. Michels and A.W. Thomas, Phys. Rev **C46** (1992) R2149

[4] H. Suganuma, S. Sasaki and H. Toki, Nucl. Phys. **B435** (1995) 207; H. Toki, H. Suganuma and S. Sasaki, Nucl. Phys. **A577** (1994) 353c.

[5] Y. Sugahara and H. Toki, Nucl. Phys. **A579** (1994) 557.