Composite nucleons in scalar and vector mean fields

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We emphasize that the composite structure of the nucleon may play quite an important role in nuclear physics. It is shown that the momentum-dependent repulsive force of second order in the scalar field, which plays an important role in Dirac phenomenology, can be found in the quark-meson coupling (QMC) model, and that the properties of nuclear matter are well described through the quark-scalar density in a nucleon and a self-consistency condition for the scalar field. The difference between theories of pointlike nucleons and composite ones may be seen in the change of the ω-meson mass in nuclear matter if the composite nature of the nucleon suppresses contributions from nucleon-antinucleon pair creation.

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It is well known that relativistic theories of nucleons interacting with mesons are very powerful in the treatment of a wide range of nuclear phenomena (Dirac phenomenology), most notably the single particle energy levels, nuclear charge densities, and elastic proton-nucleus scattering observables at intermediate energies [1–3]. The simplest and earliest example is the σ-ω model of Walecka [4] [sometimes called quantum hadrodynamics (QHD) [1]], which consists of *structureless* nucleons interacting with each other through the exchange of the scalar (σ) and the vector (ω) mesons.

These typically involve large scalar (S) and vector (V) potentials of opposite sign, which provide a number of interesting effects — e.g., a strong momentum dependence of the optical potential and an enhanced spin-orbit force [1–3,5]. One approach to understanding the physics content of Dirac phenomenology is to emphasize the role of *virtual nucleon-antinucleon* ($N\bar{N}$) pair creation. A simple estimate, up to second order in the scalar field, shows a potential which contains the effect of couplings to virtual $N\bar{N}$-pair states [2]:

$$U_{\mathrm{pair}} \approx \frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{2M_N}\frac{(S-V)^2}{2M_N}\frac{\boldsymbol{\sigma}\cdot\mathbf{p}}{2M_N} \approx \frac{\mathbf{p}^2}{2M_N^3}S^2, \tag{1}$$

if $V \approx -S$. This repulsive, strongly momentum-dependent term plays an important role in producing nuclear saturation and in enhancing the spin-orbit coupling in Dirac phenomenology. From this point of view, the excitation of virtual $N\bar{N}$ pairs (i.e., Z graphs), is a vital ingredient in the success of this approach.

However, some people have criticized the idea that $N\bar{N}$ creation should play such an important role. Brodsky [6] has argued that the pair creation should be suppressed by form factors for composite objects. Kiritsis and Seki [7] have shown that baryon loops are suppressed in the $1/N_c$ expansion of QCD. Using some tractable models, Cohen [8] has also emphasized that the composite nature of the nucleon suppresses the contribution of $N\bar{N}$ pairs compared with what is expected in the naive Dirac phenomenology. Furthermore, Prakash *et al.* [9] have shown that the composite structure of the nucleon ought to largely soften the two-loop contributions [10] in QHD. Then, is Dirac phenomenology in doubt?

Recently Wallace, Gross, and Tjon [11] have pointed out that scalar and vector interactions, which couple to a composite spin-1/2 system, obey a low-energy theorem which guarantees the same repulsive second-order interaction as given in Eq. (1). Later Birse [12] discussed it in a more general fashion, and showed, without referring to any nucleon Z graph, that not only can there be a momentum-dependent, repulsive force [as in Eq. (1)], but one may also find other types of second-order interaction which depend on the nucleon structure through various polarizabilities. It is known that in the case of the soft-photon limit of Compton scattering [13] and low-energy theorems for π-N interactions [14] quark excitations and *quark Z* graphs conspire to produce the same results as nucleon Z graphs. As Cohen has noticed [8], Dirac phenomenology depends only on the presence of strong scalar and vector potentials in the *effective* one-body optical potential, and there is no logical need for such forms to be associated with the excitation of $N\bar{N}$ pairs.

The momentum-dependent, repulsive interaction can also be seen in the quark-meson coupling (QMC) model [15,16]. In this model the properties of nuclear matter are determined by the self-consistent coupling of scalar and vector mean fields to the *quarks*, rather than the nucleons. In a simple model, where nuclear matter was considered as a collection of static, nonoverlapping bags, it was shown that a satisfactory description of the bulk properties of nuclear matter could be obtained. Furthermore, the model seems to provide a semiquantitative explanation of the Okamoto-Nolen-Schiffer anomaly [17] when quark mass differences are included [18], as well as the nuclear European Muon Collaboration (EMC) effect [19].

In the QMC model the energy of a nucleon with momen-

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tum $\mathbf{p}$ interacting with both σ and ω mean fields in the rest frame of uniform nuclear matter is given by

$$E(\mathbf{p})=g_\omega\bar{\omega}+\sqrt{\mathbf{p}^2+M_N^\star(\bar{\sigma})^2}, \tag{2}$$

where $\bar{\sigma}$ and $\bar{\omega}$ are the mean-field values, $M_N^\star$ is the effective nucleon mass, which is a function of $\bar{\sigma}$, and the vector field couples to the conserved baryon current with strength g_ω. At low nuclear density $M_N^\star$ can be expanded in terms of the scalar field as

$$M_N^\star(\bar{\sigma})=M_N+\left(\frac{dM_N^\star}{d\bar{\sigma}}\right)_{\bar{\sigma}=0}\bar{\sigma}+\tfrac{1}{2}\alpha_s\bar{\sigma}^2+\cdots, \tag{3}$$

where M_N is the free nucleon mass and α_s is the second derivative of $M_N^\star$ with respect to $\bar{\sigma}$. We can easily see that the second term on the right-hand side (RHS) of Eq. (3) is a response function to the external scalar field, and that it is given by the scalar density of a quark in the nucleon bag:

$$\left(\frac{dM_N^\star}{d\bar{\sigma}}\right)\equiv-g_\sigma C_N(\bar{\sigma})=-g_\sigma\int_{R_N}d\mathbf{r}\bar{\psi}_q\psi_q. \tag{4}$$

Here g_σ is the coupling constant of the σ field to the nucleon. [If a correction for spurious center of mass motion in the bag is taken into account [20], the RHS of Eq. (4) is modified accordingly [16].] Therefore, since

$$M_N^\star\simeq M_N-g_\sigma C_N(0)\bar{\sigma}+\tfrac{1}{2}\alpha_s\bar{\sigma}^2, \tag{5}$$

we find the nucleon energy up to $O(\bar{\sigma}^2)$ as

$$E(\mathbf{p})\simeq g_\omega\bar{\omega}+\epsilon(\mathbf{p})-g_\sigma\frac{C_N(0)M_N}{\epsilon(\mathbf{p})}\bar{\sigma}+\frac{\alpha_sM_N}{2\epsilon(\mathbf{p})}\bar{\sigma}^2+g_\sigma^2\frac{C_N(0)^2\mathbf{p}^2}{2\epsilon(\mathbf{p})^3}\bar{\sigma}^2, \tag{6}$$

where $\epsilon(\mathbf{p})=\sqrt{\mathbf{p}^2+M_N^{\star 2}}$. If we replace $g_\sigma C_N(0)\bar{\sigma}$ by the scalar potential S, the last term in Eq. (6) is indeed the momentum-dependent repulsive force pointed out by Wallace *et al.* [11] and Birse [12] [see Eq. (1)]. One can see that such a term appears in any relativistic treatment and that it arises from the modification of the nucleon mass due to the scalar field.

In our model the effect of the internal, quark structure of a nucleon can be completely absorbed into the scalar density $C_N(\bar{\sigma})$. The self-consistency condition (SCC) for the σ field is then given by

$$g_\sigma\bar{\sigma}=\frac{g_\sigma^2}{m_\sigma^2}\frac{\gamma}{(2\pi)^3}C_N(\bar{\sigma})\int^{p_F}d\mathbf{p}\frac{M_N^\star}{\sqrt{M_N^{\star 2}+\mathbf{p}^2}}, \tag{7}$$

where γ is the spin-isospin degeneracy factor, m_σ is the mass of the σ, and p_F is the Fermi momentum for the nucleon. If we set $C_N=1$, the above SCC becomes identical to that of QHD [16]. Therefore it is quite important to examine this scalar density in order to understand the difference between theories of pointlike nucleons and composite ones. In Fig. 1 C_N is shown as a function of the nuclear density, ρ_B. (The normal nuclear density is denoted by ρ_0, and the coupling constants have been chosen to reproduce the nuclear saturation properties [16].)

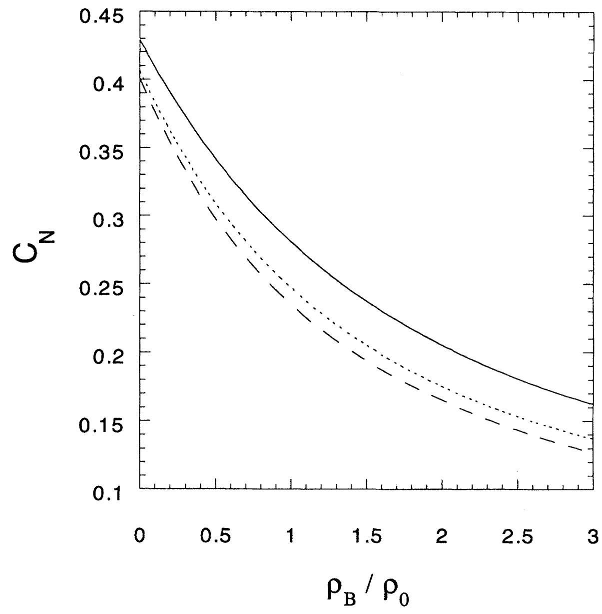

FIG. 1. Quark-scalar density for various bag radii (R_0) as a function of ρ_B. The solid, dotted and dashed curves show C_N for R_0 = 0.6, 0.8, and 1.0 fm, respectively. The quark mass is chosen to be 5 MeV.

Clearly the scalar density $C_N(\bar{\sigma})$ is much less than unity, and depends strongly on the nuclear density — as ρ_B goes higher C_N becomes smaller. This is because the small component of the quark wave function responds rapidly to the scalar field. As the scalar density itself is the source of the σ field this provides a suppression of the σ field at high density, and hence a new mechanism for the saturation of nuclear matter where the quark structure plays a vital role. Of particular interest is the fact that the internal structure of the nucleon results in a lower value of the incompressibility of nuclear matter than that obtained in approaches based on pointlike nucleons — e.g., as in QHD [1]. In fact, our prediction ($\sim$ 220 MeV) [16] is in agreement with the experimental value once the binding energy and saturation density are fixed. The effect of the quark structure of the nucleon on the spin-orbit force in finite nuclei has been discussed in Ref. [21].

One of the most topical questions which can be addressed within this model is the change of hadron properties in matter. In particular, variations in hadron masses have attracted wide interest [22–27]. It is therefore very interesting to compare the prediction of the ω-meson mass in matter by QHD [25,26] with that by the QMC model [27]. In the latter, if we suppose that the ω meson is also described by the MIT bag model in the scalar mean field (i.e., the effect of the compositeness of the ω meson is taken into account as well), the effective ω-meson mass $m_\omega^\star$ at low density is given (as in the nucleon case) by

$$m_\omega^\star\simeq m_\omega-\tfrac{2}{3}g_\sigma C_\omega(0)\bar{\sigma}, \tag{8}$$

where m_ω is the free mass of ω and $C_\omega(\bar{\sigma})$ is the quark-scalar density in the ω meson. Equation (8) means that the ω-meson mass in matter decreases as ρ_B grows: $(m_\omega^\star/m_\omega) \simeq 1-0.09(\rho_B/\rho_0)$ [27]. On the other hand, in QHD the ω-meson mass at low density is given by [26]

$$m_\omega^\star \simeq m_\omega + \frac{1}{2}\frac{\Omega^2}{m_\omega} - \frac{g_\sigma^2 m_\omega \Omega^2}{6\pi^2 m_\sigma^2}, \tag{9}$$

where $\Omega^2 = g_\omega^2 \rho_B / M_N$ is the classical plasma frequency. The second term on the RHS of Eq. (9) comes from the density-dependent part of the ω-meson propagator in random-phase approximation, which, as reported by Chin [28], leads to an *increase* in the mass. The third term, which gives a strong, attractive contribution, is due to vacuum polarization. Finally, the sum of both of these effects gives a decrease of the mass. In QHD the contribution of vacuum polarization, i.e., $N\bar{N}$ pair creation, is essential [26] to reproduce the mass reduction predicted by the QCD sum rules [24,29].

We emphasize that the origins of the mass reduction in QHD and the QMC model are completely different. As noticed by some people [6–8], if in a modified version of QHD one included the effect of nucleon substructure in suppressing the contribution of vacuum polarization the ω mass would be mainly given by the first and second terms of Eq. (9) and would *increase* in matter. In fact, it is proven that vertex corrections are quite important in QHD and that such corrections dramatically reduce the vacuum contributions in comparison with those calculated with bare vertices in two-loop calculations [9,10]. This means that in the two-loop case the nucleons are dressed with meson clouds or, more generally, they have *structure*, and that this compositeness suppresses vacuum contributions from $N\bar{N}$ loops.

In conclusion, we have argued that the composite structure of the nucleon may play quite an important role in nuclear physics. The momentum-dependent repulsive force of second order in the scalar field, which plays an important role in Dirac phenomenology, can be found in any relativistic model of composite nucleons involving scalar and vector mean fields. In the QMC model the properties of nuclear matter can be well reproduced through the quark-scalar density in the nucleon and the self-consistency condition for the scalar field. We have pointed out that theories of pointlike nucleons may be distinguishable from those involving the internal structure of the nucleon (and other hadrons) through the behavior of the ω-meson mass in matter. In particular, if $N\bar{N}$ pair creation were strongly suppressed by *the substructure of the nucleon itself*, one might even find an increase of the ω-meson mass. This is quite the opposite of the behavior found in models of composite nucleons, such as the QMC model. Clearly it would be extremely valuable to have some experimental guidance on this matter.

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