Effect of nucleon structure variation on the longitudinal response function

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Abstract

Using the quark-meson coupling (QMC) model, we study the longitudinal response function for quasielastic electron scattering from nuclear matter. In QMC the coupling constant between the scalar ($\sigma$) meson and the nucleon is expected to decrease with increasing nuclear density, because of the self-consistent modification of the structure of the nucleon. The reduction of the coupling constant then leads to a smaller contribution from relativistic RPA than in the Walecka model. However, since the electromagnetic form factors of the in-medium nucleon are modified at the same time, the longitudinal response function and the Coulomb sum are reduced by a total of about 20\% in comparison with the Hartree contribution. We find that the relativistic RPA and the nucleon structure variation both contribute about fifty-fifty to the reduction of the longitudinal response.

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There is still considerable interest in the longitudinal response for quasielastic electron scattering. Within the framework of nonrelativistic nuclear models and the impulse approximation, it is very difficult to reproduce the observed, quenched longitudinal response functions [1]. In the mid '80s, several groups calculated the longitudinal response function using Quantum Hadrodynamics (QHD) [2] (i.e., the Walecka model). They argued that the contribution of the relativistic random phase approximation (RRPA), which includes vacuum polarization, is very important in reducing the Coulomb sum rule [3, 4] below the sum of the squares of the nucleon charges in the nucleus. There have also been several other attempts to study the longitudinal response in nonrelativistic approaches [5].

On the other hand, the nucleon has internal structure, and it is nowadays expected that this structure should be modified in a nuclear environment [6]. This is closely related to the issue of chiral restoration in QCD. In QHD nuclear matter consists of point-like nucleons interacting through the exchange of point-like scalar (σ) and vector (ω) mesons. It would clearly be very interesting to investigate the quenching of the longitudinal response function in a relativistic framework, including in addition, the structural changes of the nucleon in-medium.

Recently, we have developed a relativistic quark model for nuclear matter, namely, the quark-meson coupling (QMC) model [7], which could be viewed as an extension of QHD. However, in QMC the mesons couple to confined quarks (not to point-like nucleons) and the nucleon is described by the MIT bag model. This model yields an effective Lagrangian for a nuclear system [8], which has the same form as that in QHD with a density dependent coupling constant between the σ and the nucleon (N) – instead of a fixed value. Indeed, from the point of view of the energy of a nuclear system, the key difference between QHD and QMC lies in the σ-N coupling constant, $g_s$. Although this difference may seem subtle, it leads to many attractive results [7, 8]. We have already applied this model to various nuclear problems [9]. Here we use it to study the effect of nucleon structure variation in the longitudinal response function from nuclear matter.

First, let us briefly review the calculation of the longitudinal response function for...
quasielastic electron scattering from (iso-symmetric) nuclear matter in QHD. The starting point is the lowest order polarization insertion, $\Pi_{\mu\nu}$, for the $\omega$ meson. This describes the coupling of a virtual vector meson or photon, of momentum $q$, to a particle-hole or nucleon-antinucleon excitation:

$$
\Pi_{\mu\nu}(q) = -i g_\omega^2 \int \frac{d^4 k}{(2\pi)^4} \text{Tr}[G(k)\gamma_\mu G(k+q)\gamma_\nu],
$$

(1)

where $G(k)$ is the self-consistent nucleon propagator (with momentum $k$) in relativistic Hartree approximation (RHA) given as

$$
G(k) = G_F(k) + G_D(k),
$$

(2)

$$
= (\gamma^\mu k^*_\mu + M^*) \left[ \frac{1}{k^*_{\mu\nu} - M^{*2} + i\epsilon} + \frac{i\pi}{E_k^*} \delta(k^*_0 - E_k^*)\theta(k_F - |\vec{k}|) \right].
$$

Here $k^*_{\mu\nu} = (k^0 - g_\omega V^0, \vec{k})$ ($V^0$ is the mean value of the $\omega$ field), $E_k^* = \sqrt{\vec{k}^2 + M^{*2}}$ ($M^*$ is the effective nucleon mass in matter) and $k_F$ is the Fermi momentum. Using the nucleon propagator we can separate the polarization insertion into two pieces: one is the density dependent part, $\Pi_{\mu\nu}^D$, which involves at least one power of $G_D$, and the other is the vacuum polarization insertion, $\Pi_{\mu\nu}^F$, which involves only $G_F$. The former is finite, but the latter is divergent and must be renormalized. We choose to renormalize such that $\Pi_{\mu\nu}^F(q)$ vanishes at $q^2_{\mu\nu} = m_\omega^2$ and $M^* = M$ (where $m_\omega$ and $M$ are respectively the free masses of the $\omega$ meson and the nucleon). We then find [10]

$$
\Pi_{\mu\nu}^F(q) = \xi_{\mu\nu} \Pi^F(q),
$$

(3)

with $\xi_{\mu\nu} = -g_{\mu\nu} + (q_\mu q_\nu/q^2_{\mu\nu})$ and

$$
\Pi^F(q) = \frac{g_\omega^2}{6\pi^2 q^2_{\mu\nu}} \left[ 2\ln \frac{M^*}{M} - 4 \left( \frac{M^{*2}}{q^2_{\mu\nu}} - \frac{M^2}{m_\omega^2} \right) \right]
$$

(4)

$$
+ \left( 1 + 2 \frac{M^{*2}}{q^2_{\mu\nu}} \right) f(x_q) - \left( 1 + 2 \frac{M^2}{m_\omega^2} \right) f(z_v),
$$

where $x_q = 1 - \frac{4M^{*2}}{q^2_{\mu\nu}}$, $z_v = 1 - \frac{4M^2}{m_\omega^2}$ and

$$
f(y) = \begin{cases} 
\sqrt{y} \ln \frac{\sqrt{y} + 1}{\sqrt{y}-1}, & \text{for } 1 \leq y < +\infty \\
\sqrt{y} \ln \frac{1 + \sqrt{y} - i\pi \sqrt{y}}{1 - \sqrt{y}}, & \text{for } 0 < y < 1 \\
2\sqrt{-y} \tan^{-1} \frac{1}{\sqrt{-y}}, & \text{for } y \leq 0
\end{cases}
$$

(5)
We assume that the isospin degeneracy of the vacuum is 2. For $\Pi_{\mu\nu}^D$, the explicit, analytical expressions can be found in Ref. [11] (also see Ref. [10]).

In the Hartree approximation, where only the lowest one nucleon ring is considered, the longitudinal response function, $S_L^H$, measured in electron scattering is simply given by

$$S_L^H(q) = -\left( \frac{ZG_{pE}(q)|\vec{q}|^2}{g_\pi^2\rho_Bq_\mu^2} \right) \Im\Pi_L(q). \quad (6)$$

Here $Z$ is the nuclear charge, $\rho_B$ the nuclear density, $\Pi_L(=\Pi_{33} - \Pi_{00})$ the longitudinal component of the polarization insertion (we choose the direction of $\vec{q}$ as the $z$-axis) and $G_{pE}$ is the proton electric form factor, which is usually parametrized by a dipole form in free space:

$$G_{pE}(Q^2) = \frac{1}{(1 + Q^2/0.71)^2}, \quad (7)$$

with the space-like momentum transfer, $Q^2 = -q_\mu^2$, in units of GeV$^2$. For this initial investigation we omit a small (and rather complicated) contribution from the anomalous moments [3], in order to concentrate on the role of the variation of the structure of the nucleon. Since the vacuum polarization is real in the space-like region there is no modification of the Hartree response from this term.

The RRPA for the longitudinal component of the polarization insertion, $\Pi_L^{RPA}$, involves the sum of the ring diagrams to all orders. This summation has been discussed by many authors [4, 5, 11, 13, 12]. It involves $\sigma$-$\omega$ mixing in the nuclear medium, and is given by

$$\Pi_L^{RPA}(q) = [(1 - \Delta_0 \Pi_s)\Pi_L + \Delta_0 \Pi_m^2]/\epsilon_L, \quad (8)$$

where $\epsilon_L$ is the longitudinal dielectric function

$$\epsilon_L = (1 - d_0\Pi_L)(1 - \Delta_0 \Pi_s) - (q_\mu^2/q^2)\Delta_0d_0\Pi_m^2, \quad (9)$$

with $q = |\vec{q}|$, and the free meson propagators for the $\sigma$ and $\omega$ mesons are respectively

$$\Delta_0(q) = \frac{1}{q_\mu^2 - m_\sigma^2 + i\epsilon} \quad \text{and} \quad d_0(q) = \frac{1}{q_\mu^2 - m_\omega^2 + i\epsilon}, \quad (10)$$
where \( m_\sigma \) is the \( \sigma \) meson mass. Here \( \Pi_s \) and \( \Pi_m \) are respectively the scalar and the time component of the mixed polarization insertions:

\[
\Pi_s(q) = -ig_s^2 \int \frac{d^4k}{(2\pi)^4} \text{Tr}[G(k)G(k+q)],
\]

\[
\Pi_m(q) = ig_s g_v \int \frac{d^4k}{(2\pi)^4} \text{Tr}[G(k)\gamma^0G(k+q)].
\]

The scalar polarization insertion can be again separated into two pieces. The density dependent part is finite and the explicit expression can be found in Ref. \[11\]. Because it does not involve \( G_D \), the vacuum component, \( \Pi_F^s \), is, of course, divergent and once again we need to renormalize it. First, we introduce the usual counter terms to the Lagrangian, which includes terms quadratic, cubic and quartic in the \( \sigma \) field, as well as wavefunction renormalization \[2\]. To get the “physical” properties of the \( \sigma \) meson in free space, we impose the following condition \[10\]:

\[
\Pi_F^s(q^2, M^* = M) = \frac{\partial}{\partial q^2} \Pi_F^s(q^2, M^* = M) = 0 \quad \text{at} \quad q^2 = m_\sigma^2.
\]

Then, we find

\[
\Pi_F^s(q) = \frac{3g_s^2}{2\pi^2} \left[ \frac{1}{6} (m_\sigma^2 - q_\mu^2) - \left( M^* - \frac{q_\mu^2}{6} \right) \left( 2 \ln \frac{M^*}{M} + f(x_q) - f(z_s) \right) \right.
\]

\[
+ \frac{q_\mu^2}{3} \left( \frac{M^*}{q_\mu^2} (f(x_q) - 2) - \frac{M^2}{m_\sigma^2} (f(z_s) - 2) \right)
\]

\[
- \left( M^* - M \right) (f(z_s) - 2) + 2M(M^* - M) + 3(M^* - M)^2 \right],
\]

where \( z_s = 1 - \frac{4M^2}{m_\sigma^2} \). For the mixed polarization insertion there is no vacuum polarization and it vanishes at zero density. (The explicit form can be also found in Ref. \[11\].)

As QHD involves only isoscalar mesons, the isovector RRPA response is the same as the Hartree one, eq.(6). This implies that the vacuum polarization only affects the isoscalar response. It remains to study the effect of isovector mesons. (In the isovector part the rho meson coupling (without vacuum polarization) was studied in Ref. \[13\]. It reduces \( S_L \) slightly.) Since the longitudinal response is half isoscalar and half isovector,
the longitudinal response function in RRPA is given by \[ S_{LRPA}^{\mu}(q) = - \left( \frac{ZG_{\rho E}^2(q)|q|^2}{g_{\pi \rho_B}^2q_\mu^2} \right) \Im \left[ \frac{\Pi_{LRPA}^{\mu}(q) + \Pi_{L}(q)}{2} \right]. \] (15)

Several authors [3, 4] have calculated the longitudinal response function using this RRPA polarization, and reported that it is very important in reproducing the observed experimental data [1].

Now we are in a position to discuss the effect of changes in the internal structure of the nucleon in-medium. In order to do so, we consider the following modifications to the QHD approach:

(1) meson-nucleon vertex form factor

In QHD the interactions between the mesons and nucleon are point-like. However, since both the mesons and nucleon are composite they have finite sizes. In the region of space-like momentum transfer the finite-size effect reduces the meson-N coupling. As the simplest example, one could take a monopole form factor [14] at each vertex:

\[ F_N(Q^2) = \frac{1}{1 + Q^2/\Lambda_N^2}, \] (16)

with a cut off parameter \( \Lambda_N = 1.5 \) GeV. In principle, one could self-consistently calculate the form factor within QMC. However, as such changes are not expected to make a big difference, we use eq.(16) in the following calculation.

(2) modification of the proton electric form factor

Recently we have studied the electromagnetic form factors of the nucleon, not only in free space [15] but also in a nuclear medium, using the QMC model [16] (see also Ref. [17]). Because the confined quark feels an attractive force due to the \( \sigma \), the quark wave function is modified in a nuclear medium. The ratio of the electric form factor of the proton in medium to that in free space, \( G_{pE}(\rho_B, Q^2)/G_{pE}(Q^2) \), is shown in Fig.3 in Ref. [16]. From the figure we can see that the ratio decreases very linearly as a function of \( Q^2 \), and that it is accurately parametrized at \( \rho_B = \rho_0 (= 0.15 \text{ fm}^{-3}, \text{ the normal nuclear matter density}) \) as

\[ R_{pE}(\rho_0, Q^2) \equiv \frac{G_{pE}(\rho_0, Q^2)}{G_{pE}(Q^2)} \simeq 1 - 0.26 \times Q^2. \] (17)
This implies that the (electric) rms radius of the proton at $\rho_0$ swells by about 5.5% (for more details, see Ref. [16]). Since the bag model reproduces the form factor measured in free space very well [13] and the latter is well described by eq.(7), the in-medium proton form factor can be represented as $G_{pE}(Q^2) \times R_{pE}(\rho_B, Q^2)$.

(3) density dependence of the coupling constants

In QMC the confined quark in the nucleon couples to the $\sigma$ field which gives rise to an attractive force. As a result the quark becomes more relativistic in a nuclear medium than in free space. This implies that the small component of the quark wave function, $\bar{\psi}_q$, is enhanced in medium [4, 5]. The coupling between the $\sigma$ and nucleon is therefore expected to be reduced at finite density because it is given in terms of the quark scalar charge, $\int_{Bag} dV \bar{\psi}_q \psi_q$. On the other hand, the coupling between the vector meson and nucleon remains constant, because it is related to the baryon number, which is conserved.

To study the longitudinal response of nuclear matter, we first have to solve the nuclear ground state within RHA. In QHD the total energy density for nuclear matter is written as [10]

$$E = E_0 + \frac{1}{2\pi^2} M^2 (M - M^*)^2 \left[ \frac{m_\sigma^2}{4M^2} + \frac{3}{2} f(z_s) - 3 \right],$$

(18)

where $E_0$ has the usual form (in RHA), given in Ref. [9]. Note that in Ref. [2] the renormalization condition on the nucleon loops is imposed at $q^2_\mu = 0$. The second term on the r.h.s. of eq.(18) occurs because we chose the renormalization condition for the $\sigma$ at $q^2_\mu = m_\sigma^2$ (see eq.(13)). As measurable quantities cannot depend on this choice, our model gives the same physical quantities as those of Ref. [2].

To take into account the modifications (1) and (3), we replace the $\sigma$- and $\omega$-N coupling constants in eq.(18) by

$$g_s \rightarrow g_s(\rho_B) \times F_N(Q^2),$$

(19)

$$g_v \rightarrow g_v \times F_N(Q^2),$$

(20)

The nucleon-antinucleon excitation in $\Pi_{\mu \nu}$ contributes to the photon-nucleon vertex as a RRPA correction, which may in principle lead to double counting for the form factor. However, we ignore this correction because it is very small [1].
where the density dependence of $g_s(\rho_B)$ is given by solving the nuclear matter problem self-consistently, using the MIT bag for the nucleon model (see Ref. [8]). As in QHD, we have two adjustable parameters in the present calculation: $g_s(0)$ (the $\sigma$-N coupling constant at $\rho_B = 0$) and $g_v$.

Requiring the usual saturation condition for nuclear matter, namely $E/\rho_B - M = -15.7$ MeV at $\rho_0$, we determine the coupling constants $g_s^2(0)$ and $g_v^2$ ($g_s^2(0) = 61.85$ and $g_v^2 = 62.61$). In the calculation we fix the quark mass to be 5 MeV, $m_\sigma = 550$ MeV and $m_\omega = 783$ MeV, while the bag parameters are chosen so as to reproduce the free nucleon mass ($M = 939$ MeV) with the bag radius $R_0 = 0.8$ fm (i.e., $B^{1/4} = 170.0$ MeV and $z = 3.295$ [7, 8]). This yields the effective nucleon mass $M^*/M = 0.81$ at $\rho_0$ and the incompressibility $K = 281$ MeV. (We do not consider the possibility of medium modification of the meson properties [8] in the present work.)

![Figure 1](image_url)

Figure 1: Density dependences of $g_s(\rho_B)/g_s(0)$ and $M^*/M$. The solid curve is for the ratio of the coupling constants, while the dotted curve is for the ratio of the nucleon masses.

Now we present our main results. First, in Fig. 1, we show the density dependence of the coupling constant. At $\rho_0$, $g_s$ decreases by about 9%. The effective nucleon mass is
Figure 2: Longitudinal response functions in QMC with $m_q = 5$ MeV. We fix $q = 550$ MeV and $\rho_B = \rho_0$. The dotted curve is the result of the Hartree approximation (see eq.(6)), where the effective nucleon mass is given by QMC and the proton electric form factor is the same as in free space. The dashed curve is the result of the full RRPA, without the modifications (1) and (2) (i.e. $F_N = 1$ and $R_{pE} = 1$). The dot-dashed curve shows the result of the full RRPA with the meson-N form factor but $R_{pE} = 1$. The upper (lower) solid curve shows the result of the full RRPA for $m_q = 5$ (300) MeV, including all modifications.

Next, we show the longitudinal response function in QMC. Using the density dependent coupling constant, the meson-N form factors (see eqs.(19) and (20)) and the in-medium proton electric form factor, we can calculate the longitudinal response of nuclear matter. The result is shown in Fig. 2. Because of the density dependent coupling, $g_s(\rho_B)$, the reduction of the response function due to the full RRPA (the dashed curve in the figure) from the Hartree result (the dotted curve) becomes much smaller than that in QHD. On the other hand, the modification of the proton electric form factor is very
significant, yielding a much bigger reduction in the response (see the upper solid curve). We can see that the effect of the meson-N form factor enhances the longitudinal response (see the dot-dashed curve), but it is not large.

It is also interesting to see the quark mass dependence of the longitudinal response. As an example, we consider the case of $m_q = 300$ MeV, which is a typical constituent quark mass. For $m_q = 300$ MeV and $R_0 = 0.8$ fm, the coupling constants required to fit the saturation properties of nuclear matter are: $g_s^2(0) = 68.69$ and $g_v^2 = 84.24$, and the effective nucleon mass at $\rho_0$ and the incompressibility become 723 and 345 MeV, respectively. Using these parameters we show the result for the longitudinal response (the lower solid curve) in Fig. 2. In comparison with the case $m_q = 5$ MeV, it is a little smaller and the peak position is shifted to the higher energy transfer side. This may be due to the smaller effective nucleon mass in the case $m_q = 300$ MeV than when $m_q = 5$ MeV.

Figure 3: Coulomb sum, $C(q)/Z$, at $\rho_0$ in the Hartree approximation with $R_{pE} = 1$ (the dotted curve) or the full RRPA with all modifications (the solid and dot-dashed curves are for $m_q = 5$ and 300 MeV, respectively).
The integrated strength of the longitudinal response (or the Coulomb sum), $C(q)$,

$$C(q) = \int_0^q dq_0 S_L(q, q_0),$$

is shown in Fig. 3 as a function of three-momentum transfer, $q$. For high $q$, the strength is about 20% lower in the full calculation than for the Hartree response. For low $q$, the full calculation with the constituent quark mass remains much lower than the Hartree result, while in case of the light quark mass it gradually approaches the Hartree one. This difference is caused by that the effective nucleon mass for $m_q = 5$ MeV being larger in matter than that for $m_q = 300$ MeV. The 20% reduction found here is a little smaller than the value of approximately 30% found in QHD [3, 4].

We would like to emphasize that these calculations are for nuclear matter and cannot be directly compared with the experimental data. Furthermore, there still remain discrepancies and uncertainties in the present experimental results [18, 19].

Finally, we comment on the transverse response from nuclear matter. In Ref. [16] we can see that in QMC the modification of the nucleon magnetic form factor in-medium is very small: the calculated decrease in the proton (neutron) magnetic form factor is about 1.5% (0.9%) at $\rho_0$. Therefore, one would expect the total change in the transverse response caused by RRPA correlations and the effect of the variation of the structure of the nucleon to be much smaller than in the longitudinal response. This is certainly what one needs in order to fit the experimental data [1].

In summary, we have calculated the longitudinal response of nuclear matter using the QMC model. The reduction of the $\sigma$-N coupling constant with density decreases the contribution of the RRPA, while the modification of the proton electric form factor in medium reduces the longitudinal response considerably. The longitudinal response, or the Coulomb sum, is reduced by about 20% in total, with RRPA correlations and the variation of the in-medium nucleon structure contributing about fifty-fifty. In the near future we hope to extend this work to calculate the longitudinal and transverse response functions for finite nuclei, using local density approximation, in order to compare our results directly with new experimental results [19].
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