In-Medium Nucleon Electromagnetic Form Factors in Vector Meson Dominance Model

CHEN Wen-Fang(陈文芳), LU Ding-Hui(鲁定辉)
Zhejiang Institute of Modern Physics, Zhejiang University, Hangzhou 310027

(Received 9 March 2004)

We study medium modifications of the nucleon electromagnetic form factors in the vector meson dominance model. The in-medium vector meson masses are taken from a chiral SU(3) model. We find that the electric and magnetic form factors of the bound nucleon deviate considerably from those of the free nucleon. Our results are comparable to the results from the quark meson coupling model approach and are consistent with present experimental limits.

PACS: 12.40.Vv, 13.40.Gp, 21.65.+f, 25.30.Dh

One of the fundamental issues in nuclear physics is to understand and whether and how the nuclear medium modifies the properties of the bound nucleon. Recent measurements of the polarization transfer in the electron-nucleus scattering in TJNAF/CEBAF[1] and Mainz/MAMI[2] provide strong evidence that the bound nucleon electromagnetic form factor must be modified. While early experiments, like the nuclear EMC effects and the missing strength of the response functions in nuclear quasi-elastic scattering data, can set limits on possible modifications only, the new polarization data, which have minimal sensitivity to reaction mechanisms, strongly favour medium modifications predicted by the quark meson coupling model in the fully relativistic distorted-wave impulse approximation (RDWIA).[1–3] In this Letter, we examine nuclear medium effects on the electromagnetic properties of the bound nucleon in a hybrid vector meson dominance (VMD) model.

We employ the hybrid VMD model developed by Gari and Krümpelman[4] for electromagnetic form factors of the free nucleon. In a usual VMD model, a physical photon couples with the nucleon through two possible ways: (i) a direct photon-coupling to the physical nucleon and (ii) a term involving intermediate vector mesons. At space-like momentum transfer, the model of Gari and Krümpelman incorporates the large $Q^2$ behaviour of the nucleon electromagnetic form factors by introducing an additional term. Thus it has a smooth transition from the small $Q^2$ to the large $Q^2$ region. The resulting isovector and isoscalar, $F_{1V}$ and $F_{1S}$, electromagnetic form factors are parametrized as the following:[4]

$$F_{1V}^{I}(Q^2) = \frac{g_\rho}{f_\rho} \frac{m^2}{m^2 + Q^2} F_1^{I}(Q^2) + \left[ 1 - \frac{g_\rho}{f_\rho} \right] F_1^{D}(Q^2),$$

$$F_{1S}^{I}(Q^2) = \frac{g_\omega}{f_\omega} \frac{m^2}{m^2 + Q^2} F_1^{I}(Q^2) + \left[ 1 - \frac{g_\omega}{f_\omega} \right] F_1^{D}(Q^2),$$

$$\kappa_{IV} F_2^{IV}(Q^2) = \kappa_\rho \frac{g_\rho}{f_\rho} \frac{m^2}{m^2 + Q^2} F_2^{I}(Q^2) + \left[ \kappa_{IV} - \kappa_\rho \frac{g_\rho}{f_\rho} \right] F_2^{D}(Q^2),$$

$$\kappa_{IS} F_2^{IS}(Q^2) = \kappa_\omega \frac{g_\omega}{f_\omega} \frac{m^2}{m^2 + Q^2} F_2^{I}(Q^2) + \left[ \kappa_{IS} - \kappa_\omega \frac{g_\omega}{f_\omega} \right] F_2^{D}(Q^2),$$

where $g_\rho/2$ and $g_\omega/2$ denote the $\rho NN$ and $\omega NN$ coupling constants at zero momentum transfer, respectively, and $\kappa_\rho$ and $\kappa_\omega$ are the corresponding ratios of tensor to vector coupling. Here $f_\rho$ and $f_\omega$ describe $\gamma - \rho$ and $\gamma - \omega$ couplings. The form factors $F_1^n$ and $F_1^s$ describe the corresponding meson-nucleon coupling vertices, and $F_2^n$ describes the nucleon non-resonant quark structure which is important for large momentum transfers. Considering the constraints of perturbative QCD, these form factors are parametrized as

$$F_1^n(Q^2) = \frac{A_{1^n}}{A_{1^n} + Q^2 A_{2^n} + Q^2},$$

$$F_2^n(Q^2) = \left[ \frac{A_{1^n}}{A_{1^n} + Q^2} \right]^2 \frac{A_{2^n}}{A_{2^n} + Q^2},$$

with $\tilde{Q}^2 = Q^2 [\alpha(\alpha^2 + Q^2) + 2 \omega Q_{CD} D^2 \ln (A_{1^n}^2 / A_{2^n}^2) + \alpha^2 + \omega Q_{CD}]$ and $\alpha = \rho, \omega, D$. The Sachs’s electromagnetic form factors $G^{p,n}_{M,E}$ are then expressed as

$$G_{M}^{p}(Q^2) = \frac{1}{2} \left[ F_{1V}^{I} + F_{1S}^{I} \right] + \left( \kappa_{IV} F_{2V}^{IV} + \kappa_{IS} F_{2S}^{IS} \right),$$

$$G_{E}^{p}(Q^2) = \frac{1}{2} \left[ F_{1V}^{I} + F_{1S}^{I} \right].$$
To study the medium modification of the nucleon electromagnetic form factors, the above parameters should all be re-adjusted. As a first approximation, here we focus on the effects of vector meson mass reduction; that is, replacing the $\rho$- and $\omega$-meson masses by the density-dependent ones while keeping the coupling constants and cut-off parameters intact. The in-medium properties of the vector mesons are modified by either the vacuum polarization effects\textsuperscript{[5,6]} or the changes of quark wavefunctions inside the nucleon\textsuperscript{[6]}

In the literature, the vector $\rho$NN coupling constant has been well determined in free space. The tensor coupling constant in different studies, however, is considerably different and is quite sensitive to the decrease of the $\rho$-meson mass. Hence we examine the two separate cases $\kappa_\rho = 3.425$ and $\kappa_\rho = 4.0$ in this study.

![Fig. 1. Proton electric and magnetic form factors in the medium. Here $\rho$ represents the relative nuclear matter density $\rho_B/\rho_0$. The dipole form $F_d = 1/(1 + Q^2/0.71 \text{ GeV}^2)$.](image)

Note that here an ideal $SU(3)_F$ mixing is assumed, so the $\phi$-meson is not coupled with the nucleon and does not contribute to the form factors. The vector meson masses are taken to be $m_\rho = 0.776 \text{ GeV}$, $m_\omega = 0.784 \text{ GeV}$, the photon–vector meson coupling constants $f^2_\rho/4\pi = 2.12 \pm 0.25$, $f^2_\omega/4\pi = 18.3 \pm 4.0$, and the anomalous magnetic moments $\kappa_{1\rho} = 3.706$, $\kappa_{1\omega} = -0.12$. The other parameters in the above formula are determined by fitting the experimental electromagnetic form factors of the nucleon. The results are\textsuperscript{[4]}

\[
g_\rho/f_\rho = 0.5927, \quad \kappa_\rho = 3.425, \quad A_{1(\rho,\omega)} = 0.867 \text{ GeV}, \quad A_{1D} = 1.194 \text{ GeV}, \quad A_{2(\rho,\omega,\omega)} = 2.063 \text{ GeV},
\]

\[
g_\omega/f_\omega = 0.6212, \quad \kappa_\omega = 0.3941, \quad A_{QCD} = 0.344 \text{ GeV}.
\]

![Fig. 2. Ratios of in-medium electric and magnetic form factors of the proton with respect to the free cases.](image)

| $\rho_B/\rho_0$ | 0.25 | 0.5 | 0.75 | 1.0 | 2.0 |
|-----------------|------|------|------|-----|-----|
| $m^*_\rho (\kappa_\rho = 3.425)$ | 0.581 | 0.504 | 0.471 | 0.445 | 0.428 |
| $m^*_\omega (\kappa_\rho = 3.425)$ | 0.713 | 0.681 | 0.658 | 0.642 | 0.619 |
| $m^*_\rho (\kappa_\rho = 4.0)$ | 0.616 | 0.539 | 0.508 | 0.493 | 0.470 |

We calculated nucleon electromagnetic form factors for five nuclear matter densities. The vector meson masses in the medium are taken from the recent study in the chiral $SU(3)$ model under the relativistic Hartree approximation.\textsuperscript{[6]} These are tabulated in
Table 1.

| \(\rho_B/\rho_0\) | 0.05 | 0.10 | 0.15 | 0.32 | 0.05 | 0.10 | 0.15 | 0.32 | 0.05 | 0.10 | 0.15 | 0.32 |
|----------------|------|------|------|------|------|------|------|------|------|------|------|------|
| \(r^p_E\)     | 0.902| 0.895| 0.887| 0.862| 0.923| 0.911| 0.900| 0.890| 0.940| 0.924| 0.908| 0.851|
| \(r^p_M\)     | 0.964| 0.955| 0.945| 0.911| 0.990| 0.975| 0.959| 0.905| 1.012| 0.991| 0.969| 0.892|
| \(r^p_M\)     | 0.985| 0.973| 0.961| 0.919| 1.014| 0.996| 0.976| 0.908| 1.041| 1.015| 0.988| 0.890|

For the tensor coupling \(\kappa_\rho = 3.425\), the in-medium electromagnetic form factors of the proton are shown in Fig. 1. The top two curves, which nearly overlap, are the free space form factors and the experimental dipole fit. The other three curves are for \(\rho_B/\rho_0 = 0.5,0.75,1.0\), respectively. From the order of these curves, it is clear that the in-medium form factors are suppressed as the density increases. This phenomenon is more apparent in Fig. 2, where the ratios of in-medium with respect to free space results are plotted. The medium-modified form factors of the proton are reduced by as much as \(9.3\% \sim 12.2\%\) for electric form factors and \(12.0\% \sim 15.5\%\) for magnetic form factors near \(Q^2 \sim 0.5\,\text{GeV}^2\), compared with those of the free nucleon. As \(Q^2 > 0.5\), the contributions from the non-resonant term become more and more important, so that the effect due to the vector meson mass reduction decreases and the ratio in Fig. 2 increases again.

We repeat the calculations with different \(\rho\text{NN}\) tensor coupling, \(\kappa_\rho = 4.0\). The trends of the medium effects are very much the same. The ratios of in-medium electric and magnetic form factors of the proton with respect to the free cases are shown in Fig. 3. The in-medium electric and magnetic form factors of the proton are suppressed by \(8.0\% \sim 10.2\%\) and \(12.0\% \sim 15.0\%\) at \(Q^2 \sim 0.5\,\text{GeV}^2\), respectively. The in-medium neutron magnetic form factor is also calculated. While the pattern is nearly the same, the ratio drops by \(13.2\% \sim 16.5\%\), which is slightly faster than the proton, at the same regions of the momentum transfer for both the cases of \(\kappa_\rho\).

Table 2. Electromagnetic rms radii of the nucleon in the nuclear medium at three different densities. The parameter \(a\) describes the density dependence of the vector meson coupling constants. The rms radii in free space in our calculation are \(r^p_E = 0.804\,\text{fm}\), \(r^p_M = 0.838\,\text{fm}\), and \(r^p_M = 0.829\,\text{fm}\), respectively.

| \(\rho_B/\rho_0\) | 0.5  | 0.75 | 1.0  | 0.5  | 0.75 | 1.0  | 0.5  | 0.75 | 1.0  | 0.5  | 0.75 | 1.0  |
|----------------|------|------|------|------|------|------|------|------|------|------|------|------|
| \(a\)         | 0.05 | 0.10 | 0.15 | 0.32 | 0.05 | 0.10 | 0.15 | 0.32 | 0.05 | 0.10 | 0.15 | 0.32 |
| \(r^p_E\)     | 0.902| 0.895| 0.887| 0.862| 0.923| 0.911| 0.900| 0.890| 0.940| 0.924| 0.908| 0.851|
| \(r^p_M\)     | 0.964| 0.955| 0.945| 0.911| 0.990| 0.975| 0.959| 0.905| 1.012| 0.991| 0.969| 0.892|
| \(r^p_M\)     | 0.985| 0.973| 0.961| 0.919| 1.014| 0.996| 0.976| 0.908| 1.041| 1.015| 0.988| 0.890|
Generally the vector meson coupling constants are also density dependent.\(^7,9\) The variations are strongly model-dependent. The \(\omega\)NN coupling constant is less sensitive to the density than the \(\rho\)NN coupling. To study this effect, we parametrize the density dependence of the vector meson coupling constants as follows: 
\[
g_{\rho}^{p}/g_{\rho} = 1 - a \rho_{B}/\rho_{0}, \quad g_{\omega}^{p}/g_{\omega} = 1 - a \rho_{B}/3\rho_{0}.
\]
The values of the parameter \(a\) are listed in Table 2. Generally, the larger the density, the larger the rms radii.

The \(\rho\) meson has a large width, which also varies as the density changes. This can be easily incorporated in the VMD formalism, and our analysis show that the widths of the vector mesons do not have a noticeable effect in the plots. Finally, we point out that the upward behaviour for \(Q^2 > 0.5\) is the model artifact, since we did not consider any medium effect on quark substructure. Thus our results are less reliable in large momentum transfers.

In summary, we have studied the medium modifications of the nucleon electromagnetic form factors in the hybrid VMD model. The amount of suppression is comparable to the results of the quark-meson coupling model, and hence consistent with the recent experimental analysis.

References

[1] Makov S et al 2000 Phys. Rev. C 62 057302
[2] Strauch S (JLab E93-049 collaboration) 2003 Preprint nucl-th/0308036
[3] Dieterich S et al 2001 Phys. Lett. B 500 47
[4] Lu D H et al 1999 Phys. Rev. C 60 068201
[5] Lu D H et al 1998 Phys. Lett. B 417 217
[6] Gari M and Krümpelmann W 1992 Phys. Rev. D 45 1817
[7] Gari M and Krümpelmann W 1992 Phys. Rev. D 46 484 (errata)
[8] Gari M and Krümpelmann W 1984 Phys. Lett. B 141 291
[9] Gari M and Krümpelmann W 1985 Z. Phys. A 322 689
[10] Gari M and Krümpelmann W 1986 Phys. Lett. B 173 10
[11] Kim Y, Rapp R, Brown G E and Rho M 1999 Preprint nucl-th/9902009
[12] Zschiesche D et al 2003 Preprint nucl-th/0302073
[13] Zhang Y J, Gao S and Su S K 1997 Phys. Rev. C 56 3336
[14] Saito K et al 1997 Phys. Rev. C 56 566
[15] Saito K et al 1998 Phys. Lett. B 433 243
[16] Hofmann F, Kell CM and Lenske H 2001 Phys. Rev. C 64 034314
[17] Typel S and Wolter H H 1999 Nucl. Phys. A 656 331
[18] Liu L and Ma Z Y 2002 Chin. Phys. Lett. 19 190
[19] Zhang X B and Ning P Z 2003 Chin. Phys. Lett. 20 213