Effect of bound nucleon internal structure change on nuclear structure functions

K. Tsushima\textsuperscript{a,b,c}, K. Saito\textsuperscript{d}, F.M. Steffens\textsuperscript{a,b}

\textsuperscript{a}Instituto de Física Teórica - UNESP, Rua Pamplona 145, 01405-900, São Paulo, SP, Brazil
\textsuperscript{b}Mackenzie Presbiteriana University - FCBEE, Rua da Consolação 930, 01302-907, São Paulo, SP, Brazil
\textsuperscript{c}National Center for Theoretical Sciences at Taipei, Taipei 10617, Taiwan
\textsuperscript{d}Department of Physics, Faculty of Science and Technology, Tokyo University of Science, Noda 278-8510, Japan

Abstract

Effect of bound nucleon internal structure change on nuclear structure functions is investigated based on local quark-hadron duality. The bound nucleon structure functions calculated for charged-lepton and (anti)neutrino scattering are all enhanced in symmetric nuclear matter at large Bjorken-$x$ ($x \gtrsim 0.85$) relative to those in a free nucleon. This implies that a part of the enhancement observed in the nuclear structure function $F_2$ (in the resonance region) at large Bjorken-$x$ (the EMC effect) is due to the effect of the bound nucleon internal structure change. However, the $x$ dependence for the charged-lepton and (anti)neutrino scattering is different. The former [latter] is enhanced [quenched] in the region $0.8 < x < 0.9$ [$0.7 < x < 0.85$] due to the difference of the contribution from axial vector form factor. Because of these differences charge symmetry breaking in parton distributions will be enhanced in nuclei.

\textit{PACS:} 24.85.+p, 13.60.Hb, 12.40.Nn, 13.40.Gp
\textit{Keywords:} Local quark-hadron duality, Nuclear structure functions, Bound nucleon internal structure change

I. INTRODUCTION

Recent precision data on the $F_2$ structure function in the resonance region from Jefferson Lab \cite{1}, as well as the spin asymmetry ($A_1$) data in the resonance region from HERMES \cite{2}, have significantly renewed the interest \cite{3–8} for local quark-hadron duality (local duality) \cite{9}. Before the advent of QCD, it was empirically observed by Bloom and Gilman \cite{9} that the nucleon structure function in the resonance region, $F_2^{\text{res}}$, was approximately equal to the scaling structure function, $F_2^{\text{sca}}$, measured in the deep inelastic region. The relation between the two structure functions was found to be in terms of a finite-energy sum rule. Specifically, it was observed that $F_2^{\text{res}}$ oscillates around the scaling curve, and its average is equivalent to $F_2^{\text{sca}}$ within a deviation of $\sim 10\%$. The QCD justification for the Bloom and Gilman
observation, named local duality, was made by De Rújula, Georgi, and Politzer [10]. More recent theoretical studies of local duality and QCD also have been made [11,12].

On the other hand, the European Muon Collaboration (EMC) effect [13,14] shows that the parton distributions in nuclei (bound nucleon) are different from those in a free nucleon. Basically, there happens a depletion of the structure function at intermediate and larger Bjorken-$x$ ($0.5 \lesssim x \lesssim 0.85$), while a steep rise at large Bjorken-$x$. It was concluded by Miller and Smith [15] that the depletion of the deep inelastic nuclear structure functions observed in the valence quark regime, is due to some effect beyond the conventional nucleon-meson treatment of nuclear physics [16]. We note that for the region of $x > 1$ short-range correlations as well as the nuclear binding effects become important [17].

Recent experimental data from Jefferson Lab [7] for ratios of the nuclear to deuterium cross sections in the resonance region, revealed a similar effect as that observed in the EMC effect. Because the resonance structure functions average better in nuclei due to Fermi motion and nuclear many-body effects [7], we expect that local duality is realized better in nuclei, although a proper treatment of resonances in nuclei must be investigated. Thus, local duality may potentially be one of the other new methods to study the nuclear structure functions at large Bjorken-$x$.

Complementary, the measurements of electromagnetic form factors of bound protons in polarized $(\vec{e}, \vec{e}'\vec{p})$ scattering on $^4\text{He}$ at MAMI and Jefferson Lab [18], concluded that the ratio of the electric ($G_E^p$) to magnetic ($G_M^p$) Sachs proton form factors differs by $\sim 10\%$ in $^4\text{He}$ from that in $^1\text{H}$. This strongly suggests that the internal structure of a bound proton (nucleon) is modified in nuclei. In their analyses, conventional models employing free proton form factors, phenomenological optical potentials, and bound state wave functions, as well as relativistic corrections, meson exchange currents, isobar contributions and final state interactions [18,19], all fail to account for the observed effect in $^4\text{He}$ [18]. Indeed, a better agreement with the data was obtained only when, in addition to these standard nuclear-structure corrections, a correction due to the internal structure change of a bound proton in $^4\text{He}$ was taken into account [18,20]. In Ref. [6], one of such attempts was made to extract the bound nucleon (nuclear) structure function $F_2$ at large Bjorken-$x$.

In this Letter, we extend the study of Ref. [6] to calculate also other bound nucleon structure functions for both charged-lepton and (anti)neutrino scattering based on local duality. In particular, we focus on the effect of the bound nucleon internal structure change on the nuclear structure functions. However, one of the important, conventional nuclear effects, Fermi motion, will be included in a simple Fermi gas model. We convolute the structure functions with the nucleon momentum distribution obtained in a Fermi gas model, for both the structure functions extracted using the free and bound nucleon form factors, and then calculate ratios. (To draw more solid conclusions, we need to perform an elaborated study including the nuclear effects. We plan to study the effects of binding etc. in the framework of local quark-hadron duality [21].) In addition, we consider charge symmetry breaking in parton distributions in nuclei using the structure functions calculated. For this purpose we use the bound nucleon form factors calculated [20,22] in the quark-meson coupling (QMC) model [23], which has been successfully applied to many problems of nuclear and hadronic physics [24].

Since, in the present study, we want to see the effect of the bound nucleon internal structure change included entirely in the bound nucleon form factors and the pion threshold
in a nuclear medium, the elastic contribution to the bound nucleon structure functions for charged-lepton scattering may be given by [4,11]:

\[ F_{BN}^* = \frac{1}{2}(G_M^*)^2 \delta(x - 1), \]  

\[ F_{BN}^{*2} = \frac{1}{1 + \tau} [((G_E^*)^2 + \tau (G_M^*)^2) \delta(x - 1), \]  

\[ g_{BN}^{*1} = \frac{1}{2(1 + \tau)} G_M^* (G_E^* + \tau G_M^*) \delta(x - 1), \]  

\[ g_{BN}^{*2} = \frac{\tau}{2(1 + \tau)} G_M^* (G_E^* - G_M^*) \delta(x - 1), \]  

while those for (anti)neutrino scattering for an isoscalar nucleon, \( N \equiv \frac{1}{2}(p + n) \), may be given by [25]:

\[ F_{WNBN}^{*1} = \frac{1}{4} \left[ (G_M^*)^2 + (1 + 1/\tau) (G_A^*)^2 \right] \delta(x - 1), \]  

\[ F_{WNBN}^{*2} = \frac{1}{2} \left[ \frac{(G_V^*)^2 + \tau (G_M^*)^2}{1 + \tau} + (G_A^*)^2 \right] \delta(x - 1), \]  

\[ F_{WNBN}^{*3} = G_V^* G_A^* \delta(x - 1), \]  

where \( \tau = Q^2/4M^2 \) (\( M \), the free nucleon mass) and \( x \) the Bjorken variable. \( G_E^* [G_M^*] \) is the bound nucleon electric [magnetic] Sachs form factor [20], \( G_{E,M}^* = G_{E,M}^p - G_{E,M}^n \) the corresponding isovector electromagnetic form factors, and \( G_A^* \) is the (isovector) axial vector form factor [22,25].

Using the Nachtmann variable, \( \xi = 2x/(1 + \sqrt{1 + x^2/\tau}) \), local duality equates the scaling bound nucleon structure function \( F_2^* \) and the contribution from \( F_{BN}^{*2} \) of Eq. (2):

\[ \int_{\xi_{th}^*}^{1} F_2^*(\xi)d\xi = \int_{\xi_{th}^*}^{1} F_{BN}^{*2}(\xi, Q^2)d\xi, \]  

where \( \xi_{th}^* \) is the value at the pion threshold in a nuclear medium given below. In this study we consider symmetric nuclear matter, and we can assume that the pion mass in-medium \( (m_\pi^*) \) is nearly equal to that in free space \( (m_\pi) \), and \( \xi_{th}^* \) will be given by [6]:

\[ \xi_{th}^* = \xi(x_{th}^*), \]  

with

\[ x_{th}^* = x_{th} \frac{m_\pi (2M + m_\pi) + Q^2}{m_\pi [2(M^* + 3V_\omega^* q^2) + m_\pi] + Q^2}, \quad x_{th} = \frac{Q^2}{m_\pi (2M + m_\pi) + Q^2}, \]  

where \( x_{th}^* [x_{th}] \) is the Bjorken-\( x \) at the pion threshold in medium [free space], and \( M^* \) and \( 3V_\omega^* q^2 \) [23] are respectively the effective mass and the vector potential of the bound nucleon. Inserting Eq. (2) into the r.h.s. of Eq. (8), we get [4,10]:

\[ \int_{\xi_{th}^*}^{1} F_2^*(\xi)d\xi = \frac{\xi_0^2}{4 - 2\xi_0} \left[ \frac{(G_E^*)^2 + \tau (G_M^*)^2}{1 + \tau} \right], \]  

where \( \xi_0 \) is the Nachtmann variable at the pion threshold in a nuclear medium.
where $\xi_0 = \xi(x = 1)$. The derivative in terms of $\xi^*_h$ in both sides of Eq. (11) with $\xi_0$ fixed gives [4,25]:

$$F_2^*(\xi^*_h) = F_2(x^*_h) = -2\beta^* \left[ \frac{(G_M^*)^2 - (G_E^*)^2}{4M^2(1 + \tau)^2} + \frac{1}{1 + \tau} \left( \frac{d(G_E^*)^2}{dQ^2} + \tau \frac{d(G_M^*)^2}{dQ^2} \right) \right], \quad (12)$$

where $\beta^* = (Q^4/M^2)(\xi_0^2/\xi_0^3)[(2 - \xi^*_h/x^*_h)/(4 - 2\xi_0^0)]$. Our $\beta^*$ is different from that in Ref. [4] by an extra factor $1/x^*_h$ in the limit of zero baryon density. In addition, we have an overall minus sign in the expression of Eq. (12). However, because only ratios are calculated in Ref. [4] the conclusions in there are unaffected. (These as well as the expression for $g_2$ below, have been corrected by the author [4].) Similarly, we get expressions for other bound nucleon structure functions at $x = x^*_h$:

$$F_1^*(x^*_h) = -\beta^* \frac{d(G_M^*)^2}{dQ^2}, \quad (13)$$

$$g_1^*(x^*_h) = -\beta^* \left[ \frac{G_M^*(G_M^* - G_E^*)}{4M^2(1 + \tau)^2} + \frac{1}{1 + \tau} \left( \frac{d(G_E^*)^2}{dQ^2} + \tau \frac{d(G_M^*)^2}{dQ^2} \right) \right], \quad (14)$$

$$g_2^*(x^*_h) = -\beta^* \left[ \frac{G_M^*(G_E^* - G_M^*)}{4M^2(1 + \tau)^2} + \frac{\tau}{1 + \tau} \left( \frac{d(G_E^*)^2}{dQ^2} - \frac{d(G_M^*)^2}{dQ^2} \right) \right], \quad (15)$$

$$F_1^{WN*}(x^*_h) = -\frac{\beta^*}{2} \left[ \frac{-(G_A^*)^2}{4M^2\tau^2} + \frac{d(G_M^*)^2}{dQ^2} + \frac{1 + \tau}{\tau} \frac{d(G_A^*)^2}{dQ^2} \right], \quad (16)$$

$$F_2^{WN*}(x^*_h) = -\beta^* \left[ \frac{(G_M^*)^2 - (G_E^*)^2}{4M^2(1 + \tau)^2} + \frac{1}{1 + \tau} \left( \frac{d(G_E^*)^2}{dQ^2} + \tau \frac{d(G_M^*)^2}{dQ^2} \right) + \frac{d(G_A^*)^2}{dQ^2} \right], \quad (17)$$

$$F_3^{WN*}(x^*_h) = -\beta^* \frac{(2G_M^*G_A^*)}{dQ^2}. \quad (18)$$

First, we show in Figs. 1 and 2 ratios of the bound to free nucleon structure functions without the effect of Fermi motion (dash-dotted lines), calculated for the charged-lepton scattering for baryon densities $\rho_B = \rho_0$ with $\rho_0 = 0.15$ fm$^{-3}$. Because $x_{th} = (0.7, 0.9)$ in free space (see also Eq. (10)) correspond to $Q^2 \simeq (0.65, 2.5)$ GeV$^2$, we regard the results shown in the region, $0.7 \lesssim x \lesssim 0.9$, as the present local duality predictions. The corresponding $Q^2$ range is also more or less within the reliability of the bound nucleon form factors calculated [$18,20,22$]. In the region, $0.8 \lesssim x \lesssim 0.9$, all the bound nucleon structure functions calculated, $F_{1,2}$ and $g_{s_{1,2}}$, are enhanced relative to those in a free nucleon. (We have also checked that the enhancement becomes larger as the baryon density increases.) However, the depletion observed in the EMC effect, occurring just before the enhancement as $x$ increases, is absent for all of them. Probably, the conventional binding effect, which is not entirely included in the present study, may produce some depletion [16]. (Also recall the conclusion drawn by Smith and Miller [15].) Thus, only the effect of the bound nucleon internal structure change introduced via the bound nucleon form factors and the pion threshold shift in the present local duality framework, cannot explain the observed depletion in the EMC effect for the relevant Bjorken-$x$ range $0.7 \lesssim x \lesssim 0.85$. However, it can explain a part of the enhancement at large Bjorken-$x$ ($x \gtrsim 0.85$).

In order to see whether or not the conclusions drawn above are affected by Fermi motion, we also calculate the ratios by convoluting the nucleon momentum distribution ob-
tained in Ref. [15] with the value $M = 931$ MeV. Namely, we convolute the nucleon momentum distribution with both the structure functions extracted using the free and bound nucleon form factors first, and then calculate ratios. The corresponding results are shown in Figs. 1 and 2 (dashed line, denote by ”with Fermi”). Note that, because the upper value of $x_{th}(x_{th}^{\text{max}} \sim 0.91)$ is limited for a reliable extraction of the structure functions by the reliable $Q^2$ range for the nucleon elastic form factors in this study, we had to cut the contribution from the region, $x_{th} \geq x_{th}^{\text{max}}$, in the convolution integral. This would effectively suppress the enhanced part of the bound nucleon structure functions. The obtained results show a similar feature, except the region $x_{th} \gtrsim 0.8$. However, even the region $x_{th} \gtrsim 0.8$, the enhancement feature remains the same. Thus, we conclude that, the enhancement of the bound nucleon structure functions $F_{1,2}^{W \gamma N}$ and $g_{1,2}^{\gamma}$ in the charged lepton scattering obtained, is intrinsic and not smeared by the effect of Fermi motion. This is more obvious in the region $0.7 \lesssim x_{th} \lesssim 0.8$. In that region, the effect of Fermi motion is nearly canceled out in the ratios, as one could expect.

Next, we show in Fig. 3 the bound nucleon structure functions calculated from a charged current, $F_{1,2,3}^{W \gamma N}$, together with those in vacuum for the (anti)neutrino scattering. For a reference, we show also $\frac{18}{5} F_2^{\gamma N} \equiv \frac{18}{5} \left( F_2^{p} + F_2^{n} \right)$ in vacuum for the charged-lepton scattering. The effect of Fermi motion is included in the same way as that was included in the charged-lepton scattering case. Similarly to the charged-lepton scattering case, $F_{1,2,3}^{W \gamma N}$ in symmetric nuclear matter are enhanced at large $x$ without the effect of Fermi motion, but only in the region, $0.85 \lesssim x \lesssim 0.9$. This is due to the contribution from the in-medium axial vector form factor $G_A^*$. Although $G_A^*$ falls off faster than the free space $G_A$ in the range $Q^2 \lesssim 1$ GeV$^2$, the $Q^2$ dependence turns out to be slightly enhanced in the range $Q^2 \gtrsim 1$ GeV$^2$, due to the Lorentz contraction of the internal quark wave function of the bound nucleon [22]. Then, the contribution from the $Q^2 \gtrsim 1$ GeV$^2$ region gives a suppression. (See Eqs. (16) - (18), but neglecting small contributions from the non-derivative terms with respect to $Q^2$, which are suppressed by $\sim 1/\tau^2$ as $Q^2$ increases.) With the effect of Fermi motion, the enhancement and quenching features at $x_{th} \gtrsim 0.8$ are less pronounced because of the convolution procedure applied in the present treatment.

After having calculated $F_2^*$ for both the charged-lepton and (anti)neutrino scattering, we can now study charge symmetry breaking in parton distributions focusing on the effect of the bound nucleon internal structure change, with and without the effect of Fermi motion. In free space, it was studied in Ref. [25] based on the local duality. A measure of charge symmetry breaking in parton distributions at $x = x_{th}$ may be given by [25]:

$$
\left[ \frac{5}{6} F_2^{W \gamma N}(x_{th}^*) - 3 F_2^{\gamma N}(x_{th}^*) \right] = 3 \left\{ \frac{13}{18} \beta^* \left[ \frac{d(G_M^p)^2}{dQ^2} + \frac{d(G_M^n)^2}{dQ^2} \right] + \frac{5}{9} \beta^* \frac{d(G_M^p G_M^n)}{dQ^2} - \frac{5}{18} \beta^* \frac{d(G_A^*)^2}{dQ^2} \right\} . \quad (19)
$$

In Fig. 4 we show normalized ratios, divided by $\frac{1}{2} \left[ \frac{5}{6} F_2^{W \gamma N} + 3 F_2^{\gamma N} \right]$, for baryon densities $\rho_B = 0$ and $\rho_0$ with and without the effect of Fermi motion. The results show that the charge symmetry breaking in symmetric nuclear matter is enhanced due to the effect of the bound nucleon internal structure change. (We have checked that the breaking becomes larger as the baryon density increases.) Note that, because the quantity is the ratio by definition, it is very insensitive to the effect of Fermi motion in entire region of $x_{th}$ considered. Thus,
charge symmetry breaking looks to be more appreciable in nuclei than in the case of a free nucleon, and/or could affect fragmentation in heavy ion collisions. In particular, the results imply that the NuTeV anomaly [26], which was observed in the measurements using iron target, would be enhanced even more than the analysis made [25] in free space. (See e.g., Ref. [27] for detailed discussions.) However, the present status of experimental accuracies would not allow to detect the effect distinctly.

We summarize the results and conclusions of the present study based on the local quark-hadron duality:

1. The effect of the bound nucleon internal structure change in the nuclear medium is to enhance the bound nucleon structure functions at large Bjorken-\(x\) (\(x \gtrsim 0.85\)) for the charged-lepton scattering and especially \(F_{1W}^{WN}\) in (anti)neutrino scattering.

2. The \(x\) dependence of the bound nucleon structure functions obtained for the charged-lepton scattering and \(F_{2,3W}^{WN}\) in (anti)neutrino scattering is different. Namely, the former [latter] is enhanced [quenched] in the region \(0.8 \lesssim x \lesssim 0.9\) [\(0.7 \lesssim x \lesssim 0.85\)].

3. Only the effect of the bound nucleon internal structure change cannot explain the depletion observed in the EMC effect (for the charged-lepton scattering) for the relevant Bjorken-\(x\) range in this study, \(0.7 \lesssim x \lesssim 0.85\), but it can explain a part of the enhancement occurring in the larger region of \(x\).

4. Charge symmetry breaking in parton distributions in nuclei, or higher baryon densities, would be enhanced relative to that in free space due to the internal structure change of a bound nucleon.

5. The conclusions obtained above are insensitive to the effect of Fermi motion in the treatment of the present study.

Finally, we again note that the present study have not included in a rigorous manner the conventional nuclear effects, such as binding and Fermi motion. (This will be investigated in future work [21].) However, even solely from the present results, we can conclude/suggest that, not only the conventional nuclear effects, but also the effect of the bound nucleon internal structure change, may be appreciable in various nuclear structure functions at large Bjorken-\(x\).

Acknowledgment: We would like to thank W. Melnitchouk for the correspondence on Ref. [4]. KT was supported by FAPESP (03/06814-8), and FMS was supported by FAPESP (03/10754-0), CNPq (308032/2003-0) and Mackpesquisa.
REFERENCES

[1] I. Niculescu et al., Phys. Rev. Lett. 85 (2000) 1182;
    I. Niculescu et al., Phys. Rev. Lett. 85 (2000) 1186;
    S.A. Wood, Nucl. Phys. B (Proc. Suppl.) 112 (2002) 63.
[2] A. Airapetian et al. (HERMES Collaboration), Phys. Rev. Lett. 90 (2003) 092002.
[3] R. Ent, C.E. Keppel, I. Niculescu, Phys. Rev. D 62 (2000) 073008.
[4] W. Melnitchouk, Phys. Rev. Lett. 86 (2001) 35, (E) ibid 93 (2004) 199901; Nucl. Phys. A 680 (2001) 52c.
[5] F.E. Close, N. Isgur, Phys. Lett. B 509 (2001) 81;
    N. Isgur et al., Phys. Rev. D 64 (2001) 054005;
    S. Liuti et al., Phys. Rev. Lett. 89 (2002) 162001;
    F.E. Close, W. Melnitchouk, Phys. Rev. C 68 (2003) 035210;
    N. Bianchi, A. Fantoni, S. Liuti, Phys. Rev. D 69 (2004) 014505;
    S. Jeschonnek, J.W. Van Orden, Phys. Rev. D 69 (2004) 054006.
[6] W. Melnitchouk, K. Tsushima, A.W. Thomas, Eur. Phys. J. A 14 (2002) 105.
[7] J. Arrington et al., nucl-ex/0307012.
[8] For a recent review, W. Melnitchouk, R. Ent, C.E. Keppel, hep-ph/0501217, to be published in Phys. Rep.
[9] E.D. Bloom and F.J. Gilman, Phys. Rev. Lett. 25 (1970) 1140; Phys. Rev. D 4 (1971) 2901.
[10] A. De Rújula, H. Georgi, H.D. Politzer, Ann. Phys. (New York) 103 (1997) 315; Phys. Rev. D 15 (1977) 2495.
[11] C.E. Carlson, N.C. Mukhopadhyay, Phys. Rev. D 41 (1990) 2343; Phys. Rev. Lett. 74 (1995) 1288; Phys. Rev. D 58 (1998) 094029.
[12] X. Ji, P. Unruau, Phys. Lett. B 333 (1994) 228; Phys. Rev. D 52 (1995) 72;
    X. Ji, W. Melnitchouk, Phys. Rev. D 56 (1997) R1.
[13] J. Aubert et al., Phys. Lett. B 123 (1982) 275;
    A. Bodek et al., Phys. Rev. Lett. 51 (1983) 534;
    R.G. Arnold et al., Phys. Rev. Lett. 52 (1984) 727.
[14] For a review, e.g., M. Arneodo, Phys. Rep. 240 (1994) 301;
    D.F. Geesaman, K. Saito, A.W. Thomas, Ann. Rev. Nucl. Part. Sci. 45 (1995) 337 (1995).
[15] G.A. Miller, J.R. Smith, Phys. Rev. C 65 (2001) 015211; (E) ibid C 66 (2002) 049903.
[16] K. Saito, A.W. Thomas, Nucl. Phys. A574 (1994) 659.
[17] K. Saito, Prog. Theor. Phys. 82 (1989) 18;
    L.L. Frankfurt, M.I. Strikman, D.B. Day, M. Sargsyan, Phys. Rev. C48 (1993) 2451.
[18] S. Dieterich et al., Phys. Lett. B 500 (2001) 47 (2001);
    R.D. Ransome, Nucl. Phys. A 699 (2002) 360c;
    S. Strauch et al., Phys. Rev. Lett. 91 (2003) 052301;
    S. Strauch (E93-049 Coll.), Eur. Phys. J. A 19 (2004) 153.
[19] J.J. Kelly, Phys. Rev. C 60 (1999) 044609;
    J.M. Udias, J.R. Vignote, Phys. Rev. C 62 (2000) 034302;
    J.M. Udias et al., Phys. Rev. Lett. 83 (1999) 5451.
[20] D.H. Lu et al., Phys. Lett. B 417 (1998) 217;
    D.H. Lu et al., Phys. Rev. C 60 (1999) 068201.
[21] K. Saito, K. Tsushima, F.M. Steffens, work in progress.
[22] K. Tsushima, Hungchong Kim, K. Saito, Phys. Rev. C 70 (2004) 038501;
     D.H. Lu, A.W. Thomas, K. Tsushima, nucl-th/0112001.
[23] P.A.M. Guichon, Phys. Lett. B 200 (1989) 235;
     K. Saito, A.W. Thomas, Phys. Lett. B327 (1994) 9;
     P.A.M. Guichon et al., Nucl. Phys. A 601 (1996) 349;
     K. Saito, K. Tsushima, A.W. Thomas, Nucl. Phys. A 609 (1996) 339; Phys. Rev. C 55
     (1997) 2637.
[24] K. Tsushima et al., nucl-th/0301078; Nucl. Phys. A 630 (1998) 691; Phys. Lett. B 429
     (1998) 239; (E) ibid. B 436 (1998) 453; Phys. Lett. B 443 (1998) 26; Phys. Rev. C 59
     (1999) 2824; Phys. Rev. C 62 (2000) 064904; J. Phys. G 27 (2001) 349;
     F.M. Steffens et al., Phys. Lett. B 447 (1999) 233;
     K. Saito et al., Phys. Lett. B 460 (1999) 17; Phys. Lett. B 465 (1999) 27;
     A. Sibirtsev et al., Phys. Lett. B 484 (2000) 23; Eur. Phys. J. A 6 (1999) 351;
     K. Tsushima, F. Khanna, J. Phys. G 30 (2004) 1765; Phys. Rev. C67 (2003) 015211;
     Phys. Lett. B 552 (2003) 138; Prog. Theor. Phys. Suppl. 149 (2003) 160;
     K. Saito, K. Tsushima, Phys. Lett. B 575 (2003) 4;
     P.A.M. Guichon, A.W. Thomas, Phys. Rev. Lett. 93 (2004) 132502.
[25] F.M. Steffens, K. Tsushima, Phys. Rev. D 70 (2004) 094040.
[26] G.P. Zeller et al., Phys. Rev. Lett. 88 (2002) 091802.
[27] J.T. Londergan, A.W. Thomas, hep-ph/0407247.
FIG. 1. Ratios for the charged-lepton scattering structure functions $F_{1,2}^*/F_{1,2}$, those extracted using the bound and free nucleon form factors. Effect of Fermi motion is included by the convolution with the nucleon momentum distribution [15] for both the structure functions extracted using the free and bound nucleon form factors, and then ratios are calculated (the dashed lines denoted by "with Fermi").
FIG. 2. Same as Fig. 1, but for $g_{1,2}/g_{1,2}$. 
FIG. 3. Structure functions calculated for (anti)neutrino scattering (for an isoscalar nucleon), for baryon density $\rho_B = 0$ and $\rho_0$. For a reference, $\frac{18}{5} F_2^{N} \equiv \frac{18}{5} (F_2^p + F_2^n)$ for the charged-lepton scattering in vacuum is also shown (top panel). Ratios are shown for both with and without the effect of Fermi motion. (See also caption of Fig. 1 for the effect of Fermi motion.)
FIG. 4. Normalized ratios, divided by $\frac{1}{2} \left[ \frac{5}{6} F^W_{2N^*} + 3F^\gamma_{2N^*} \right]$, for charge symmetry breaking in parton distributions, for baryon densities $\rho_B = 0$ and $\rho_0$, with and without the effect of Fermi motion. (See also caption of Fig. 1 for the effect of Fermi motion.)