European Muon Collaboration effect: Nuclear-binding effect or vivid quark signature?

Bo-Qiang Ma
Center of Theoretical Physics, China Center of Advanced Science and Technology (World Laboratory), Beijing, China and Institute of High Energy Physics, Academia Sinica, P.O. Box 918(4), Beijing 100039, China
(Received 9 July 1990)

A relativistic two-level convolution model for deep-inelastic lepton nucleus scattering is presented in which the target nucleus is considered as a composite system of baryon-mesons which are also composite systems of quark-gluons, with each level based on the light-cone quantum field theory, respectively. In this prescription the impulse approximation is justified, the baryon number conservation is naturally guaranteed, and the off-shell ambiguity in the nucleonic approach is fixed. The scaling variable for bound nucleons is derived in a realistic way from the constraint of overall "energy" conservation, and a two-level convolution formula for nuclear-structure functions is given. It is shown that the European Muon Collaboration effect seems unable to be explained by the off-shell effect in terms of nucleonic degrees of freedom alone in this prescription.

I. MOTIVATION

The nuclear European Muon Collaboration (EMC) effect[1] was recognized as a clear quark signature in nuclei[2] at the time when it was discovered. Many models were proposed to explain the observed data by introducing non-nucleonic degrees of freedom such as nucleon swelling or overlap,[3] multiquark cluster,[4] color conductivity,[5] and π or Δ degrees of freedom,[6] etc. However, the situation has been more or less blurred since the appearance of a conventional nucleonic model[7] in which the EMC effect can be interpreted in terms of nucleonic degrees of freedom only if, besides the momentum distribution (Fermi motion), the removal energy distribution (nuclear binding) of nucleons is also taken into account. Although some discussions about a duality between nucleon swelling and nuclear binding have been given[8] in order to ease the conflict between them, a natural conclusion[9] drawn from the apparent success of the conventional approach is that there is no urgency to introduce non-nucleonic degrees of freedom in explaining the EMC effect.

Frankfurt and Strikman (FS),[10] however, have argued that, when relativistic effects are consistently taken into account by considering in the normalization of the vertex functions the effect arising from the baryon number conservation, the contribution of the nuclear binding to the EMC effect should be strongly reduced. A calculation of the nuclear-structure function based on the Hartree-Fock description of nuclei with the correct normalization of the vertex functions and the proper average single-particle energy by Li, Liu, and Brown[11] stressed the conclusion of FS. But Ciofi degli Atti and Liuti recently showed[12] that the nucleon correlations resulting from realistic *NN* interactions strongly increase the values of the mean removal and kinetic energies of nucleons in nuclei and, hence, a reasonable explanation of the EMC data in terms of nucleonic degrees of freedom can again be recovered even when the flux factor arising from the normalization of the vertex functions is considered.

Nevertheless, there are still two disadvantages in the conventional nucleonic approach which are actually recognized by some,[13–16] but are not seriously taken for granted commonly. The first disadvantage[13,14] is that the applicability of the impulse approximation has not seriously been justified. The conventional approach may be good in evaluating the bulk of the nuclear structure function, but the contributions from final-state interactions, which were not seriously justified to be negligible, may prevent it from giving reliable results of the detailed properties such as the EMC effect. The second disadvantage is that there are ambiguities of how to identify the off-mass-shell structure functions with the on-mass-shell structure functions, and it is possible that a good fit of the data may come from the special assumptions in identifying the off-mass-shell structure functions rather than from the realistic physical mechanism.[15,16] It is obvious, however, that until the contributions from nuclear binding and Fermi motion can be reliably calculated in solving the two disadvantages, one will never be sure that the conventional nucleonic approach is correct or incorrect.[16]

Bearing the above considerations in mind, we present in this paper a relativistic two-level convolution model for deep-inelastic lepton nucleus scattering in which the target nucleus is considered as a composite system of baryon-mesons with the constituent baryon-mesons also being composite systems of quark-gluons, supplying each level described in the light-cone quantum field theory[17] as a baryon-meson field and a quark-gluon field, respectively. This model can be considered as a phenomenal realization of one of the motivations of Brodsky *et al.*[18] to understand the nuclear baryon-meson degrees of freedom in terms of the fundamental interaction of quark-gluons from quantum chromodynamics (QCD). The light-cone quantum field theory is based on the light-front Hamiltonian dynamics[19] in which $x^+=t+z$ is the new "time" coordinate and $p^-=p_t-p_z$ is the new "energy" variable. It is argued in Ref. 14, based on the fact that light-front dynamics in an ordinary frame is equivalent to instantform dynamics in the infinite momentum frame,[20] that the Einstein time dilatation effect[21] will remove the final-state interactions if we specify the light-cone four-momentum variable of the target nucleus P_μ and of the virtual photon q_μ as

$$P_\mu=(P^+,P^-,\mathbf{P}_\perp)=(M_A,M_A,\mathbf{O}_\perp)\ ,$$
$$q_\mu=(q^+,q^-,\mathbf{q}_\perp)=(0,2\nu,\mathbf{q}_\perp)\ , \tag{1}$$

provided with the defining equation

$$q^2=-Q^2,\ \ P\cdot q=M_A\nu\ . \tag{2}$$

This justifies the applicability of the impulse approximation. We will also show later on that the off-mass-shell ambiguity in the conventional approach is also specified in this model since the scaling variable for bound nucleons is derived in the light-cone quantum field theory in a way similar to that in which the Bjorken scaling variable was derived in the quark-parton model for free nucleons,[22] with the off-"energy"-shell effect of struck nucleons also considered.

II. MODEL CALCULATION

In neglecting the quark interference corresponding to the quark exchange contributions, which will not be discussed further in this paper, we can illustrate, following Refs. 14 and 22, the contributions to the hadronic tensor $W^A_{\mu\nu}$ for the target nucleus in Fig. 1, where the kinematics for the constituent baryon-mesons and quark-gluons is parametrized as

$$p_\mu=(p^+,p^-,\mathbf{p}_\perp)=[yP^+,(M^2+\mathbf{p}_\perp^2)/yP^+,\mathbf{p}_\perp] \quad \text{for baryon-mesons}\ ,$$
$$k_\mu=(k^+,k^-,\mathbf{k}_\perp)=[xp^+,(m^2+\mathbf{k}_\perp^2)/xp^+,\mathbf{k}_\perp] \quad \text{for quark-gluons}\ . \tag{3}$$

Using the light-cone rules[17] with the notations adopted in Ref. 14, we obtain

$$W^A_{\mu\nu}=\sum_{BM}\int\frac{d^2\mathbf{p}_\perp dp^+}{16\pi^3p^+}\frac{\rho_{BM}(\mathbf{p})}{y}\times\sum_q\int\frac{d^2\mathbf{k}_\perp dk^+}{16\pi^3k^+}\frac{\rho_q(\mathbf{k})}{x}w_{\mu\nu}(k,k')\ . \tag{4}$$

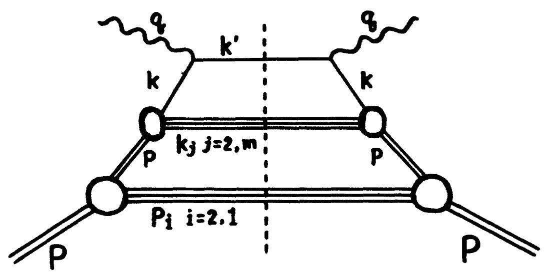

FIG. 1. The contributions to the hadronic tensor $W^A_{\mu\nu}$ for the nucleus in the relativistic two-level convolution model.

The x,y in the denominator of (4) are essentially corresponding to the flux factors[10-12] which guarantee baryon number conservation, $\rho_{BM}(\mathbf{p})$ is the momentum distribution of baryons and mesons in the nuclear bound state with $\mathbf{p}=(p^+,\mathbf{p}_\perp)$ being the light-cone kinematic three-momentum, $\rho_q(\mathbf{k})$ is the quark momentum distribution in the struck baryon or meson, and $w_{\mu\nu}(k,k')$ is the hadronic tensor of the on-mass-shell struck quark with its kinematics before and after the scattering being k_μ and k'_μ, respectively, supplying k'_μ subjects to the constraint of overall four-momentum conservation between the virtual photon and the target nucleus:

$$\mathbf{k}'_\perp=\mathbf{q}_\perp+\mathbf{k}_\perp\ ,$$
$$k'^+=q^++k^+\ , \tag{5}$$
$$k'^-+\sum_{j=2}^{m}k_j^-+\sum_{i=2}^{l}p_i^-=P^-+q^-\ .$$

To obtain $F_2^A=\nu W_2^A$, we calculate only the $++$ component of $W^A_{\mu\nu}$ since the instantaneous fermion lines do not contribute to it as indicated by Brodsky *et al.*[17] Hence, we obtain the two-level convolution formula

$$F_2^A(\nu,Q^2)=\sum_{BM}\int\frac{d^2\mathbf{p}_\perp dp^+}{16\pi^3p^+}\rho_{BM}(\mathbf{p})F_2^B(\nu,Q^2)\ , \tag{6}$$

in which

$$F_2^B(\nu,Q^2)=\sum_q\int\frac{d^2\mathbf{k}_\perp dx}{16\pi^3x}\delta(x-x_B)x\rho_q(\mathbf{k})Q_q^2\frac{q^-}{q^-+k^-} \tag{6a}$$

is the structure function for the bound hadron and x_B, defined to be k^+/p^+, is the scaling variable for bound hadrons. x_B is obtained from the overall "energy" conservation condition[22]

$$\frac{[m^2+(\mathbf{k}_\perp+\mathbf{q}_\perp)^2]}{(k^++q^+)}+\sum_{j=2}^{m}k_j^-+\sum_{i=2}^{l}p_i^-=\frac{(M_A^2+\mathbf{P}_\perp^2)}{P^+}+q^-\ . \tag{7}$$

Substituting $\sum_{j=2}^{m}k_j^-$ and $\sum_{i=2}^{l}p_i^-$ by p_c^- and P_C^-, the minus component momenta of the residual hadron and nucleus spectators treated as effective particles with effective mass m_c and M_C, respectively, we have

$$x_B=(A-B)/2C\ , \tag{8}$$

in which

$$A=C+m^2+(\mathbf{k}_\perp+\mathbf{q}_\perp)^2-m_c^2-(\mathbf{p}_\perp-\mathbf{k}_\perp)^2\ ,$$
$$B=\{A^2-4C[m^2+(\mathbf{k}_\perp+\mathbf{q}_\perp)^2]\}^{1/2}\ , \tag{8'}$$
$$C=[M_A^2+2M_A\nu-(\mathbf{p}_\perp^2+M_C^2)/(1-y)]/y\ .$$

It should be noticed that the scaling variable for bound hadrons (i.e., x_B) is different from that for free ones (i.e., x_P in Ref. 22) because the bound hadrons are off-"energy"-shell. In the Bjorken limit $Q^2\to\infty$ and $\nu\to\infty$, with $x=Q^2/2M\nu$ fixed, x_B reduces to

$$x_B = Q^2/2M_A \nu y \ . \tag{9}$$

From Ref. 22 we know the structure function for the free nucleon

$$F_2^N(\nu,Q^2) = \sum_q \int \frac{d^2\mathbf{k}_\perp dx}{16\pi^3 x} \delta(x - x_P) x \rho_q(\mathbf{k}) Q_q^2 \frac{q^-}{q^- + k^-} \ . \tag{10}$$

One sees, in comparing with Eq. (6a), that there are no ambiguities in identifying the structure functions for bound hadrons with those for free ones unless there are "intrinsic" distortions in the quark momentum distribution for bound hadrons caused by nuclear environment (e.g., nucleon swelling). Although the constituents are on-mass-shell, they are off-"energy"-shell and subject to overall "energy" conservation. In this sense, the binding effect (i.e., off-"energy"-shell effect) is also included in the two-level convolution formula (6). The contributions from nuclear binding are contained in M_C in the scaling variable x_B; it gives Q^2 power-law-type contributions and hence can be neglected if Q^2 and ν are sufficiently large.[22] It becomes clear that the above result is contrary to that of the conventional nucleonic approach, which gives a scaling variable $x = Q^2/2p\cdot q$ for bound nucleons with a strong binding dependence even when Q^2 and ν are very large because p_μ is off-mass-shell in that case.

III. NUMERICAL RESULTS

The hadron constituents such as π, Δ, etc., of the nucleus other than nucleons can be ascribed as higher multihadron Fock state contributions in the model. Since this paper aims to investigate whether the nuclear-binding and Fermi motion effects are able to explain the EMC effect in terms of nucleonic degrees of freedom alone, the use of the minimal multihadron Fock state is adequate for our purpose. Figure 2 presents the calculated ratio $F_2^A(x,Q^2)/F_2^N(x,Q^2)$, where $x = Q^2/2M\nu$ is the Bjorken variable, in the model with the input nucleon structure function $F_2^N(x,Q^2)$ taken from Ref. 23 and the nucleon momentum distribution $\rho_{BM}(\mathbf{p})$ approximated from the nonrelativistic wave function following the Berger-Coester method.[24] One sees that the contributions from the Fermi motion and nuclear binding in terms of nucleonic degrees of freedom alone are not able to explain the EMC effect, as can be explained in the conventional nucleonic approach.[7] The approximations in $\rho_{BM}(\mathbf{p})$ will not change the conclusion because a change of k_F from 260 to 400 MeV does not change the calculated ratio much. Hence, we seem to reveal an unexpectedly large prescription dependence in the calculated off-shell effect in nuclear models, as has also recently been discovered by Kisslinger and Johnson.[25]

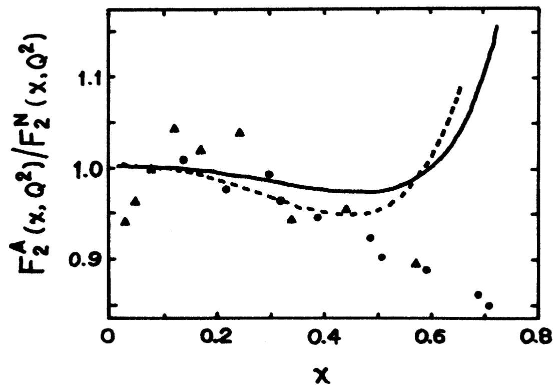

FIG. 2. The calculated ratio $F_2^A(x,Q^2)/F_2^N(x,Q^2)$ in the relativistic two-level convolution model. The value of the nuclear Fermi momentum k_F is 260 MeV for the solid curve and 400 MeV for the dashed curve. The ● are the Stanford Linear Accelerator Center data for A=Fe [$Q^2=5$ (GeV/c)^2, $8<\epsilon<24.5$ GeV] and the ▲ are the new EMC data for A=Cu [4.4 (GeV/c)$^2 < Q^2 < 40.4$ (GeV/c)^2, $\epsilon = 120-280$ GeV] from Ref. 1, respectively.

IV. SUMMARY

In summary, we present in this paper a relativistic two-level convolution model dealing with deep-inelastic lepton nucleus scattering at the quark level in which the contributions from Fermi motion and nuclear binding can also be calculated. Two disadvantages in the conventional approach are avoided in this prescription, and it gives a two-level convolution formula which is convenient to study further, besides the Fermi motion and nuclear-binding effects, non-nucleonic degrees of freedom such as the "intrinsic" distortions of the quark momentum distributions in bound nucleons, and pionic or other baryonic degrees of freedom in nuclei, etc. A first study in terms of minimal multihadron Fock state showed that the EMC effect is not able to be explained by the nuclear-binding and Fermi motion effects in terms of nucleonic degrees of freedom alone, and this implies a large prescription dependence in the calculated off-shell effect in nuclear models.

ACKNOWLEDGMENTS

The author acknowledges the useful discussions with Prof. T. Huang, Prof. G. L. Li, and Prof. J. Sun. He also acknowledges the encouraging and inspiring discussions with Prof. L. S. Kisslinger, Prof. M. B. Johnson, Prof. G. B. West, and Prof. H. J. Weber.

[1]EM Collaboration, J. J. Aubert *et al.*, Phys. Lett. **123B**, 275 (1983); A. Bodek *et al.*, Phys. Rev. Lett. **50**, 1431 (1983); **51**, 534 (1983); EM Collaboration, J. Ashman *et al.*, Phys. Lett. B **202**, 603 (1988).
[2]R. L. Jaffe, Phys. Rev. Lett. **50**, 228 (1983).
[3]See, e.g., R. L. Jaffe, F. Close, R. Roberts, and G. Ross, Phys. Lett. **134B**, 449 (1984).
[4]See C. E. Carlson and T. J. Havens, Phys. Rev. Lett. **51**, 261

(1983).
[5]See O. Nachtmann and H. J. Pirner, Z. Phys. C **21**, 277 (1984).
[6]C. H. Llewellyn Smith, Phys. Lett. **128B**, 107 (1983); M. Ericson and A. W. Thomas, *ibid.* **128B**, 112 (1983); J. Szwed, *ibid.* **128B**, 245 (1983).
[7]S. V. Akulinichev *et al.*, Phys. Rev. Lett. **55**, 2239 (1985); J. Phys. G **11**, L245 (1985); Phys. Lett. **158B**, 485 (1985).
[8]F. E. Close, R. G. Roberts, and G. G. Ross, Phys. Lett. **168B**, 400 (1986); R. P. Bickerstaff and G. A. Miller, *ibid.* **168B**, 409 (1986).
[9]R. P. Bickerstaff and A. W. Thomas, Phys. Rev. D **35**, 108 (1987).
[10]L. L. Frankfurt and M. I. Strikman, Phys. Lett. B **183**, 254 (1987).
[11]G. L. Li, K. F. Liu, and G. E. Brown, Phys. Lett. B **213**, 531 (1988).
[12]C. Ciofi degli Atti and S. Liuti, Phys. Lett. B **225**, 215 (1989).
[13]R. L. Jaffe, Comments Nucl. Part. Phys. **13**, 39 (1984).
[14]B.-Q. Ma and J. Sun, J. Phys. G **16**, 823 (1990); B.-Q. Ma, Mod. Phys. Lett. A **6**, 21 (1991).
[15]M. B. Johnson and J. Speth, Nucl. Phys. **A470**, 488 (1987); L. S. Kisslinger and M. B. Johnson, Phys. Rev. C **36**, 1081 (1987); V. V. Anisovich *et al.*, Nucl. Phys. **A468**, 429 (1989).
[16]A. W. Thomas, Prog. Part. Nucl. Phys. **20**, 21 (1987).
[17]S. J. Brodsky, in *Lectures on Lepton Nucleon Scattering and Quantum Chromodynamics,* edited by A. Jaffe and D. Ruelle (Birkhäuser, Boston, 1982), p. 255; S. J. Brodsky, T. Huang, and G. P. Lepage, in *Particles and Fields,* edited by A. Z. Capri and A. N. Kamal (Plenum, New York, 1983), p. 143.
[18]See S. J. Brodsky, Comments Part. Nucl. Phys. **12**, 213 (1984).
[19]P. A. M. Dirac, Rev. Mod. Phys. **21**, 392 (1949).
[20]L. Susskind, Phys. Rev. **165**, 1535 (1968); K. Bardakci and M. B. Halpern, *ibid.* **176**, 1686 (1968).
[21]L. Susskind, Phys. Rev. Lett. **21**, 944 (1968).
[22]B.-Q. Ma, Phys. Lett. B **176**, 179 (1986); B.-Q. Ma and J. Sun, Int. J. Mod. Phys. A **6**, 345 (1991).
[23]D. W. Duke and J. F. Owens, Phys. Rev. D **30**, 49 (1984).
[24]E. L. Berger and F. Coester, in *Workshop on Nuclear Chromodynamics,* edited by S. J. Brodsky and E. J. Moniz (World-Scientific, Singapore, 1986), p. 255. See also, E. L. Berger, F. Coester, and R. B. Wiringa, Phys. Rev. D **29**, 398 (1984); E. L. Berger and F. Coester, *ibid.* **32**, 1071 (1985).
[25]L. S. Kisslinger and M. B. Johnson (unpublished).