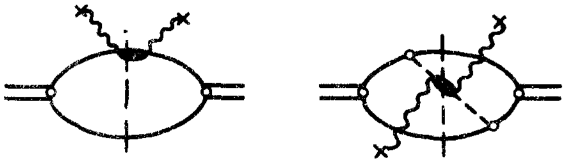
Meson exchange currents in deep inelastic scattering by a deuteron

L. P. Kaptar', B. L. Reznik, A. I. Titov, and A. Yu. Umnikov
Joint Institute for Nuclear Research

(Submitted 22 February 1988; resubmitted 4 April 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 9, 428–431 (10 May 1988)

The principal diagrams which determine the meson corrections to the structure function of the deuteron $F_2^D(x)$ have been calculated. The contribution of the one-pion and two-pion exchange to $F_2^D(x)$ has been determined. Allowance for the meson currents is shown to restore only half the energy sum rule, which is violated by the off-shell effects of the nucleons, for the quark distribution of the deuteron.

1. It is clear that meson exchange currents should contribute to deep inelastic scattering of electrons by nuclei in a manner similar to their contribution in other nuclear processes.[1–4] It is hardly surprising, therefore, that mesons are the prime candidates used to explain the EMC (European Muon Collaboration) effect, the observed deviation from unity of the ratio of the structure functions of the heavy nucleus and the deuterium $R^{A/D}$. It was assumed that because of the strong interaction of nucleons, the heavy nuclei have an excess of mesons (pions) δn_M per nucleon, in comparison with the noninteracting nucleons, and this excess was used to explain the increase in $R^{A/D}$ at $x \lesssim 0.2$ (Refs. 5–7). A weak point of these experimental studies was the fact that δn_M was not calculated but given either as a parameter or as a function of the unknown quantities which themselves were effective parameters. In practical terms, this means that the quantitative contribution of nuclear mesons to the structure function has not yet been determined. Although the self-consistent theory of meson ex-



a b

FIG. 1. Diagrams of the deep inelastic scattering by a deuteron.

change currents in deep inelastic scattering by heavy nuclei will take some time to construct, the salient qualitative features of this theory can now be studied by using the "exactly solvable nuclear model" of the deuteron as an example. In this letter we will calculate the contribution of meson exchange currents to the deep inelastic scattering by a deuteron.

2. Since the hadron tensor $W^D_{\mu\nu}$, which contains all the information on the deep inelastic scattering, is determined by the imaginary part of the amplitude of elastic scattering of a virtual γ-ray quantum by a deuteron, we can use the theory of meson exchange currents which was developed for the description of the elastic scattering of electrons by the lightest nuclei.[1,2,4] The impulse-approximation diagrams and the meson-exchange-current diagrams, which in turn are comprised of the diagrams for meson currents, transfer currents, renormalization currents, etc., contribute to the deep inelastic scattering cross section and to the elastic scattering cross section. It can be shown[4] that some of the meson-exchange-current diagrams cancel out and some of them are taken into account in the impulse-approximation diagrams, so that $W^D_{\mu\nu}$ can ultimately be represented as a sum of the impulse-approximation diagram and the meson-current diagrams shown respectively in Figs. 1a and 1b. Self-consistency of the theory implies that the mesons generating the NN interaction in the deuteron should be taken into account in the calculation of the meson-current diagrams. In our calculations we used two potentials: the one-boson-exchange potential $(\pi+\sigma+\omega+\rho+\delta+\eta)$ of the "Bonn" group[8] and the "Paris" potential,[9] which at $r>0.8$ fm is given by the exchange potential $\pi+2\pi+\omega$ and which at $r<0.8$ fm is affected by a phenomenological repulsion.

3. Calculation of the structure function of the deuteron in the impulse approximation reduces to the calculation of the convolution

$$F_2^{ND}(x) = \int F_2^N(x/\xi)\varphi(\xi)\,d\xi, \tag{1}$$

where $F_2^N(x)$ is the structure function of the nucleon, and $\varphi(\xi)$ is the distribution of bound nucleons in the deuteron in the fraction of the longitudinal momentum $\xi=(p_0+p_3)/M$ and $p_0=M_D-(M^2+\mathbf{p}^2)^{1/2}$. The distribution $\varphi(\xi)$ satisfies the condition for normalization to the baryon charge[10] and is related to the wave function of the deuteron[11]:

$$\varphi(\xi) = \int (1+p_3/M)\,|\psi_D(\mathbf{p})|^2\,\delta\left(\xi-\frac{p_0+p_3}{M}\right)\frac{d^3p}{(2\pi)^3}\,. \tag{2}$$

For F_2^N we used the parametrization

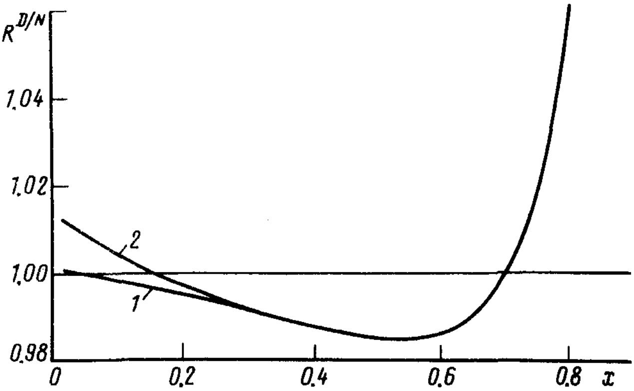


FIG. 2. Ratio of the structure functions of the deuteron and nucleon (the wave function of the deuteron in the Bonn potential was used in the calculation). Curve 1—$R^{ND/N} = F_2^{ND}/F_2^N$; curve 2—$R^{D/N} = (F_2^{ND} + \delta F_2^{\pi D} + \delta F_2^{2\pi D})/F_2^N$.

$$F_2^N(x) = \frac{5}{18}\,(x^{0,58}(2{,}69\,(1-x)^{2,7} + 1{,}56(1-x)^{3,7}) + 0{,}8(1-x)^7).$$

The result of the calculation of $F_2^{ND}(x)$ is shown in Fig. 2 as a ratio $R^{ND/N} = F_2^{ND}/F_2^N$ (curve 1). Qualitatively, $R^{ND/N}$ behaves exactly the same way as the ratio of the structure functions of the heavy nucleus and heavy nucleon,[12] although the depth of the minimum at $x \approx 0.5$–0.7 is much shallower in this case because of the relatively low deuteron binding energy. The nucleon cohesion leads to the familiar (see, e.g., Ref. 11) violation of the energy sum rule:

$$\int F_2^{ND}(x)dx = (1-\delta)\int F_2^N(x)\,dx, \tag{3}$$

where the calculation using the wave function of the deuteron in the Bonn and Paris potentials gives $\delta_B = 4.7\times 10^{-3}$ and $\delta_p = 5.0\times 10^{-3}$.

4. The contribution of one-pion exchange to the structure function is given by

$$\delta F_2^{\pi D} = \int \frac{d^3p_1\, d^3p_2}{(2\pi)^6}\,\frac{(k_0+k_3)}{\sqrt{2E_1 2E_2}\,M}\,F_2^{\pi}\left(\frac{xM}{(k_0+k_3)}\right)\frac{g_\pi^2(k)}{(k^2-m_\pi^2)^2}$$

$$\Phi(\mathbf{p}_1\,\mathbf{p}_2)\theta(k_0+k_3), \tag{4}$$

where m_π is the pion mass, $k = (k_0,\mathbf{k}) = (M_D - E_1 - E_2,\ \mathbf{p}_1 + \mathbf{p}_2)$ is its 4 momentum, $g_\pi(k)$ is the vertex function of the pion-nucleon interaction,[8,9] M is the nucleon mass, M_D is the deuteron mass, and $E_{1,2} = (M^2 + \mathbf{p}_{1,2}^2)^{1/2}$. For F_2^π we used the parametrization $F_2^\pi(x) = [5\times 0.75\sqrt{x}(1-x) + 20\times 0.075(1-x)^5]/9$. The function $\Phi(\mathbf{p}_1,\mathbf{p}_2)$ is related to the S and D components of the deuteron wave function u and w by the relation

$$\Phi(\mathbf{p}_1,\mathbf{p}_2) = 4\pi\Big\{\mathbf{k}^2\big[2f(p_1)f(p_2)\big] - 3\big[u(p_1)u(p_2) + w(p_1)w(p_2)P_2(\cos\theta)\big]$$

$$+\ 2\big[P_2(\cos\theta)-1\big]\big[\mathbf{p}_1^2 f(p_1)w(p_2) + \mathbf{p}_2^2 f(p_2)w(p_1)\big]\Big\},$$

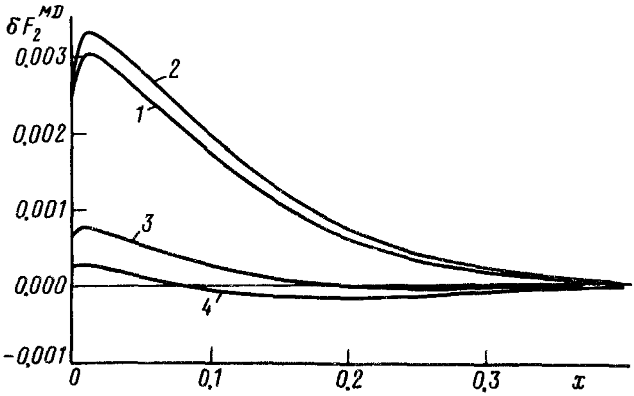


FIG. 3. Contribution of meson currents to the structure function of the deuteron. Curves 1 and 2—$\delta F_2^{\pi D}$; curves 3 and 4—$\delta F_2^{2\pi D}$ (curves 1 and 3—calculation in the Bonn potential; curves 2 and 4—calculation in the Paris potential).

where $f(p) = w(p) + \sqrt{2}u(p)$, $p = |p|$, θ is the angle between $\mathbf{p}_1$ and $\mathbf{p}_2$, and $\mathbf{P}_2(\cos\theta)$ is a Legendre polynomial. The results of the calculations of $\delta F_2^{\pi D}(x)$ are shown in Fig. 3 (curves 1 and 2). The more massive 2π and ω meson contributions, as opposed to the one-pion contribution, are suppressed. For illustration, we show in Fig. 3 (curves 3 and 4) the calculation of the contribution from the 2π exchange current which was approximated, as usual, by the scalar σ-meson exchange.[8] Figure 2 (curve 2) shows the result of the calculation of the ratio

$$R^{D/N} = (F_2^{ND} + \delta F_2^{\pi D} + \delta F_2^{2\pi D}) / F_2^N .$$

We see that allowance for the meson currents leads to an increase in $R^{D/N}$ at $x \lesssim 0.25$. The meson currents determine the energy sum rule only partially ($\sim 60\%$), since $(\langle x\rangle_\pi^D + \langle x\rangle_{2\pi}^D)/\langle x\rangle_N \approx 3\times 10^{-3}$. The deviation of $\langle x\rangle_D/\langle x\rangle_N$ from unity is attributable to a violation of self-consistency of the calculation: In realistic potentials the domain occupied by the core is defined essentially phenomenologically.

Our study thus shows that a nucleus described as a system which is comprised exclusively of nucleons is an incomplete description. The same conclusion based on a qualitative analysis of the EMC effect was drawn by Karmanov.[13] Inclusion of the meson component leads to the meson-current diagrams. The behavior of the structure function when only the nucleon component (the impulse approximation) is taken into account resembles the EMC effect qualitatively at $x > 0.25$ and it violates the energy sum rule. The meson currents partially correct this violation, leaving room for other mechanisms: activation of the convolution model, renormalization of the vertex MNN function, allowance for the contribution of the multiquark structure of the deuteron at small NN distances, etc.

We wish to thank V. K. Luk'yanov, V. V. Burov, V. A. Karmanov, M. Kirschbach, E. M. Levin, and E. L. Bratkovska for useful discussions.

[1]M. Chemtob, in: Mesons in Nuclei, Amsterdam, North-Holland, 1979, p. 555.
[2]E. A. Ivanov and É. Truglik, Fiz. Elem. Chastits At. Yadra **12**, 492 (1981) [Sov. J. Part. Nucl. **12**, 198 (1981)].

[3]M. Kirchbach and E. Truglik, Fiz. Elem. Chastits At. Yadra **17**, 224 (1986) [Sov. J. Part. Nucl. **17**, 93 (1986)].
[4]M. Gari and H. Hyuga, Z. Phys. **A277**, 291 (1976).
[5]M. Ericson and A. W. Thomas, Phys. Lett. **B128**, 112 (1983).
[6]A. I. Titov, Yad. Fiz. **40**, 76 (1984) [Sov. J. Nucl. Phys. **40**, 50 (1984)].
[7]É. E. Sapershteĭn and M. Zh. Shmatikov, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 44 (1985) [JETP Lett. **41**, 53 (1985)].
[8]R. Machleidt *et al.*, Phys. Rep. **149**, 1 (1987).
[9]M. Lacombe *et al.*, Phys. Rev. **C21**, 861 (1980).
[10]L. L. Frankfurt and M. I. Strikman, Phys. Rep. **76**, 215 (1981).
[11]B. L. Birbraur *et al.*, Mat. XXI Winter School, Institute of Nuclear Physics, Leningrad, 1986, p. 3.
[12]S. V. Akulinichev *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 105 (1985) [JETP Lett. **42**, 127 (1985)].
[13]V. A. Karmanov, in: Proceedings of a Symposium on Nucleon-Nucleon and Hadron-Nucleus Interactions at Intermediate Energies, Institute of Nuclear Physics, Leningrad, 1986, p. 496.

Translated by S. J. Amoretty