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STRUCTURE FUNCTIONS OF THE DEUTERON WITH ALLOWANCE FOR MESON EXCHANGE CURRENTS WITHIN QCD-VMD MODEL

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1 Introduction

The analysis of the structure functions of the deuteron in the elastic eD-scattering at large transfer momenta is important for investigation of the nucleus when the extension structure of the latter is taken into account.

It was shown before that the behavior of $A(q^2)$, $B(q^2)$ and tensor polarization $T_{20}(q^2)$ at high momentum transfer is determined by non-nucleon degrees of freedom: meson exchange currents (MEC) [1]-[4] and quark degrees of freedom [5]- [7] in nonrelativistic approaches and in approaches allowing for relativistic effects [8], [9].

In fact, for the analysis not only the inclusion of different degrees of freedom but also the structure of NN - interaction is of great importance.

At present, there exist many approaches for the description of the strong NN-interaction [10]-[14]. Among them one group of models attracts our special attention which consists of field-theoretical meson-exchange models. Within these approaches the NN-interaction is described as a one-boson-exchange system where the field-theoretical Hamiltonian is a sum of Feynman diagrams including various meson exchanges. Now three kinematical scales are determined [12]: "classical" (long-range $r > 2fm$), "dynamical" ($1fm < r < 2fm$), and "phenomenological" (short-range $r < 1fm$) regions. The classical region is defined by one-pion exchange. The heavier-meson exchanges dominate in the dynamical region. The region of $r < 1fm$ (core region) takes into account different processes, for instance, quark-gluon exchanges. The phenomenological region is the most interesting for further discussion since it has a direct relation to the problem of the extended structure of the nucleon. Still the question of the hadron structure is open. QCD effectively describes the region inside the confinement radius, and the outside dynamics is well described by the interaction of mesons with a core. It is a problem to describe consistently the in-outside regions.

In the paper [15], the model of the nucleus potential describes the NN-interaction within a similar QCD-VMD picture [16]. This is the field - theoretical model of NN interaction where the one-boson-exchange (OBE) potential is constructed by introducing the vertex form factors $F_{1,2}(q^2)$. The presence of vertex form factors is dictated, first, by the quark structure of the nucleons, and second, by the mesons dynamics. The form factor is a function of the so-called cut-off mass Λ that governs the range of influence of non-nucleon degrees of freedom. The following approximation for vertex form factors is used in ref. [15]:

$$F_{1,2}(q^2) = \frac{\Lambda_1^2}{\Lambda_1^2 + Q^2}\left(\frac{\Lambda_2^2}{\Lambda_2^2 + Q^2}\right)^{1,2}, \tag{1}$$

where

$$Q^2 = k^2 \frac{\log\left(\frac{\Lambda_2^2 + k^2}{\Lambda_{QCD}^2}\right)}{\log\left(\frac{\Lambda_2^2}{\Lambda_{QCD}^2}\right)} . \tag{2}$$

The scale $\Lambda_1 = 800$ MeV is taken into account for all mesons. The quark-gluon scale is: $\Lambda_2 = 2.85$ GeV, $\Lambda_{QCD} = 0.29$ GeV. The vertex form factor $F_1(q^2)$ is used for πNN, $\pi N\Delta$, $\rho N\Delta$ and the vector part of ρNN interaction and $F_2(q^2)$, for its tensor parts. The nucleon structure is calculated in two kinematical scales: the low q^2 (meson exchange) and high q^2 (quark-gluon exchange). It

was shown that higher mass meson exchanges become important when the nucleon structure is taken into account. These exchanges are described by a sort of contact relations leading to contact interactions of nucleons. We quote the important result of paper [15]: it was shown that the description of meson-exchange nucleon-nucleon interaction leaves little room for a sizeable contribution of the conventional boson-exchange at small distances. Apart from the dominance of the pion-exchange at large distances a heavier (than pion) meson-exchange is overshadowed at the medium range by the direct interaction of physical nucleons. The nucleon-nucleon interaction has three scales: i) the scale given by the pion mass (140 MeV), ii) the meson scale (800 MeV) which determines the size of the nucleon, and iii) the quark-gluon scale (2.85 GeV). Experimental data on the structure functions $A(q^2)$ and $B(q^2)$ in the elastic eD- scattering [17],[18] allow one to make calculations within the model taking the deuteron structure into account in detail.

In our paper the structure functions $A(q^2)$, $B(q^2)$ and tensor polarization $T_{20}(q^2)$ are calculated within the QCD-VMD model [15]. The functions were calculated with allowance for isoscalar exchange currents: pair current, current of the $\rho\pi\gamma$ process and the retardation current. The expediency of such a choice was studied in detail in papers [2], [4].

2 Basic Formulas

The differential cross-section of elastic electron-deuteron scattering has the form:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[A(q^2) + B(q^2)\tan^2\frac{\theta}{2}\right], \tag{3}$$

where

$$A(q^2) = F_C^2(q^2) + F_Q^2(q^2) + \frac{2}{3}\eta F_M^2(q^2), \tag{4}$$

$$B(q^2) = \frac{4}{3}\eta(1+\eta)F_M^2(q^2), \tag{5}$$

where $\eta = q^2/4M^2$ and M is the mass of the deuteron. The charge $F_C(q^2)$, quadrupole $F_Q(q^2)$ and magnetic $F_M(q^2)$ form factors are determined by the following equation:

$$F_{C,Q,M} = F^{imp}_{C,Q,M} + F^{\pi NN}_{C,Q,M} + F^{\rho\pi\gamma}_{C,Q,M} + F^{ret,\pi}_{C,Q,M}, \tag{6}$$

where F^{imp} is the impulse approximation, $F^{\pi NN}$ stands for the pair current, $F^{\rho\pi\gamma}$ denotes the $\rho\pi\gamma$ process, and $F^{ret,\pi}$ stands for the retardation current. Analytical expressions for individual contributions have the next forms. The impulse parts of $F_{C,Q,M}$ are:

$$F_C^{imp} = G_E^S(q^2)\int_0^\infty (u^2(r) + w^2(r))j_0(qr/2)dr, \tag{7}$$

$$F_Q^{imp} = \frac{6\sqrt{2}M^2}{q^2}G_E^S(q^2)\int_0^\infty (2u(r)w(r) - w^2(r)/\sqrt{2})j_2(qr/2)dr, \tag{8}$$

where $G_E^S(q^2)$ is the electric form factor:

$$G_E^S(q^2) = G_E^p(q^2) + G_E^n(q^2), \tag{9}$$

$G_E^p(q^2)$ ($G_E^n(q^2)$) is the electric form factor of a proton (neutron).

$$\begin{aligned} F_M^{imp} &= 2G_M^S(q^2)\left\{\int_0^\infty dr[u^2(r) - w^2(r)/2]j_0(qr/2)\right. \\ &+ \left.\int_0^\infty dr[u(r)w(r)/\sqrt{2} + w^2(r)/2]j_2(qr/2)\right\} \\ &+ \frac{3}{2}G_E^S(q^2)\int_0^\infty dr[u^2(r)j_0(qr/2) + w^2(r)j_2(qr/2)]. \end{aligned} \tag{10}$$

$$G_M^S(q^2) = G_M^p(q^2) + G_M^n(q^2), \tag{11}$$

where $G_M^p(q^2)$ ($G_M^n(q^2)$) is the magnetic form factor of a proton (neutron) (u(r) and w(r) are S, D wave functions of the deuteron). Pair approximations have the following expressions:

$$\begin{aligned} F_C^{\pi NN}(q^2) = &-\frac{g^2_{\pi NN}}{16m^3\pi^2}qG_M^S(q^2)\int_0^\infty k^2\,dk\{(\frac{1}{2}qJ_0^\pi + kJ_1^\pi)\times \\ &\times(I^0_{00}(k) + I^0_{22}(k)) + (qJ_2^\pi + 2kJ_1^\pi)(-2\sqrt{2}I^2_{20}(k) + I^2_{22}(k))\} \end{aligned} \tag{12}$$

$$\begin{aligned} F_Q^{\pi NN}(q^2) = &\frac{3g^2_{\pi NN}M^2}{4m^3\pi^2 q}G_M^S(q^2)\int_0^\infty k^2\,dk\{(\frac{1}{2}qJ_0^\pi + kJ_1^\pi)\times \\ \times &\ (I^0_{00}(k) + \frac{1}{10}I^0_{22}(k)) + \frac{1}{\sqrt{2}}(\frac{1}{2}qJ_2^\pi + kJ_1^\pi)I^2_{20}(k) + \\ + &\ \frac{11}{28}(\frac{1}{2}qJ_2^\pi + \frac{28}{55}kJ_1^\pi + \frac{27}{55}kJ_3^\pi)I^2_{22}(k) + \frac{54}{35}(\frac{1}{2}qJ_4^\pi + kJ_3^\pi)I^4_{22}(k)\} \end{aligned} \tag{13}$$

$$\begin{aligned} F_M^{\pi NN}(q^2) &= -\frac{g^2_{\pi NN}}{8m^3\pi^2}G_M^S(q^2)\int_0^\infty dk\,k^2\{k^2(J_0^\pi - J_2^\pi)[I^0_{00}(k) - \frac{1}{2}I^0_{22}(k)] - \\ &- [k^2(J_0^\pi - J_2^\pi) + \frac{9}{20}kq(J_1^\pi - J_3^\pi)][\sqrt{2}I^2_{20}(k) + I^2_{22}(k)]\} \end{aligned} \tag{14}$$

where

$$I^l_{LL'}(k) = \int_0^\infty u_L(r)u_{L'}(r)j_l(kr)\,dr. \tag{15}$$

and $u_{L=0} \equiv u(r)$, $u_{L=2} \equiv w(r)$.

The functions J_l^π depend on the meson nucleon form factor.

$$J_l^\pi = \int_{-1}^{1} dx P_l(x) \frac{F_{1,\pi NN}^2(k^2+q^2/4+qkx)}{k^2+q^2/4+qkx+m_\pi^2} \tag{16}$$

The charge $F_C(q^2)$, quadrupole $F_Q(q^2)$ and magnetic $F_M(q^2)$ form factors for $\rho\pi\gamma$- current are determined by the following equations:

$$\begin{aligned} F_C^{\rho\pi\gamma}(q^2) &= \frac{C_{\rho\pi\gamma}}{3\pi^2} q^2 K_{\rho\pi\gamma}(q^2) \int_0^\infty dk k^3 \{k(J_0^{\rho\pi\gamma} - J_2^{\rho\pi\gamma})[I_{00}^0(k) + I_{22}^0(k)] + \\ &+ \frac{1}{2}[k(J_0^{\rho\pi\gamma} - J_2^{\rho\pi\gamma}) + \frac{9}{10}q(J_1^{\rho\pi\gamma} - J_3^{\rho\pi\gamma})][-2\sqrt{2}I_{20}^2(k) + I_{22}^2(k)]\}, \end{aligned} \tag{17}$$

$$\begin{aligned} F_Q^{\rho\pi\gamma}(q^2) &= -\frac{C_{\rho\pi\gamma}M^2}{\pi^2 q} K_{\rho\pi\gamma}(q^2) \int_0^\infty dk k^3 \{[qk(J_0^{\rho\pi\gamma} - J_2^{\rho\pi\gamma}) + \\ &+ \frac{18}{5}k^2(J_1^{\rho\pi\gamma} - J_3^{\rho\pi\gamma})][I_{00}^0(k) + \frac{1}{10}I_{22}^0(k)] - \sqrt{2}[qk(J_0^{\rho\pi\gamma} - J_2^{\rho\pi\gamma}) - \\ &- \frac{9}{5}(k^2 + \frac{q^2}{4})(J_1^{\rho\pi\gamma} - J_3^{\rho\pi\gamma})]I_{20}^2(k) - \frac{2}{5}[qk[(J_0^{\rho\pi\gamma} - J_2^{\rho\pi\gamma}) - \\ &- \frac{81}{49}(J_2^{\rho\pi\gamma} - J_4^{\rho\pi\gamma})] - \frac{9}{14}(k^2 + \frac{q^2}{4})(J_1^{\rho\pi\gamma} - J_3^{\rho\pi\gamma})]I_{22}^2(k) + \\ &+ \frac{162}{245}[qk(J_2^{\rho\pi\gamma} - J_4^{\rho\pi\gamma}) - \frac{28}{5}k^2(J_1^{\rho\pi\gamma} - J_3^{\rho\pi\gamma}) + \\ &+ \frac{35}{18}q^2(J_3^{\rho\pi\gamma} - J_5^{\rho\pi\gamma})]I_{22}^4(k)\}, \end{aligned} \tag{18}$$

$$\begin{aligned} F_M^{\rho\pi\gamma}(q^2) &= -\frac{g_{\pi NN}g_{\rho NN}g_{\rho\pi\gamma}}{m_\rho \pi^2} K_{\rho\pi\gamma}(q^2) \int_0^\infty dk\, k^2 \{(k^2(J_0^{\rho\pi\gamma} - J_2^{\rho\pi\gamma}) \times \\ &\times [I_{00}^0(k) - \frac{1}{2}I_{22}^0(k)] - [k^2(J_0^{\rho\pi\gamma} - J_2^{\rho\pi\gamma}) + \frac{9}{20}kq(J_1^{\rho\pi\gamma} - J_3^{\rho\pi\gamma})] \times \\ &\times [\sqrt{2}I_{20}^2(k) + I_{22}^2(k)]\}, \end{aligned} \tag{19}$$

where

$$J_l^{\rho\pi\gamma} = \int_{-1}^{1} dx P_l(x) R \frac{F_{1,\rho NN}(k^2+q^2/4-qkx)F_{1,\pi NN}(k^2+q^2/4+qkx)}{(k^2+q^2/4-qkx+m_\rho^2)(k^2+q^2/4+qkx+m_\pi^2)}, \tag{20}$$

$$R = (1 + k_v \frac{\Lambda_2^2}{\Lambda_2^2 + Q^2}), \tag{21}$$

(Q^2 from (2) with $k^2 = k^2 + q^2/4 - qkx$) for $F_{C,Q}^{\rho\pi\gamma}$ ($k_v = 6$) and

$$J_l^{\rho\pi\gamma} = \int_{-1}^{1} dx P_l(x) \frac{F_{1,\rho NN}(k^2+q^2/4-qkx)F_{1,\pi NN}(k^2+q^2/4+qkx)}{(k^2+q^2/4-qkx+m_\rho^2)(k^2+q^2/4+qkx+m_\pi^2)}, \tag{22}$$

for $F_M^{\rho\pi\gamma}$ form factors. The retardation current leads to the next equations:

$$\begin{aligned} F_C^{ret,\pi}(q^2) &= \frac{g_{\pi NN}^2}{16\pi^2 m^3} q F_1^S(q^2) \int_0^\infty dr\, j_1(qr/2)\{-I_1(r)[u^2(r) + w^2(r)] + \\ &+ \frac{2}{5}[-2I_1(r) + 3I_3(r)][2\sqrt{2}u(r)w(r) - w^2(r)]\}, \end{aligned} \tag{23}$$

$$F_Q^{ret,\pi}(q^2) = -\frac{6g_{\pi NN}^2}{5m\pi^2 q} F_1^S(q^2) \int_0^\infty dr\, [j_1(qr/2)A_1(r) + j_3(qr/2)A_2(r)], \tag{24}$$

$$\begin{aligned} A_1(r) &= -I_1(r)u^2(r) - \frac{\sqrt{2}}{10}[-2I_1(r) + 3I_3(r)]u(r)w(r) + \\ &+ \frac{1}{4}[I_1(r) + 6I_3(r)]w^2(r), \end{aligned} \tag{25}$$

$$\begin{aligned} A_2(r) &= -\frac{3}{2}I_3(r)u^2(r) + \frac{3\sqrt{2}}{20}[3I_1(r) + 8I_3(r)]u(r)w(r) - \\ &- \frac{3}{8}[-3I_1(r) + 2I_3(r)]w^2(r). \end{aligned} \tag{26}$$

The functions $I_1(r)$ and $I_2(r)$ depend on the meson-nucleon form factor

$$I_l(r) = \int_0^\infty dk\, k^5 j_l(kr) \frac{F_{1,\pi NN}^2(k^2)}{(k^2+m_\pi^2)^2}. \tag{27}$$

$$F_M^{ret,\pi}(q^2) = \frac{9g_{\pi NN}^2}{85m^3\pi^2} q G_M^S(q^2) \int_0^\infty dr\, [j_1(qr/2)B_1(r) + j_3(qr/2)B_2(r)], \tag{28}$$

$$\begin{aligned} B_1(r) &= \frac{2}{3}u^2(r)I_1(r) + \frac{1}{5}\{\sqrt{2}u(r)w(r)[\frac{1}{3}I_1(r) - 3I_3(r)] - \\ &- w^2(r)[\frac{4}{3}I_1(r) + 3I_3(r)]\}, \end{aligned} \tag{29}$$

$$B_2(r) = -\frac{2}{3}u^2(r)I_3(r) + \frac{1}{5}\{\sqrt{2}u(r)w(r)[2I_1(r) - \frac{4}{3}I_3(r)] - - w^2(r)[2I_1(r) + \frac{1}{3}I_3(r)]\}, \quad (30)$$

F_1^S is the isoscalar form factor of a proton, $G_M^S = (1 + k_S)G_E^S$, $k_S = -0.12$,

$$G_E^S = (1 + \frac{q^2}{0.71GeV^2})^{-2} \quad (31)$$

$$K_{\rho\pi\gamma} = (1 + \frac{q^2}{m_\omega^2})^{-1}, \quad (32)$$

$$C_{\rho\pi\gamma} = -\frac{g_{\rho NN}g_{\pi NN}g_{\rho\pi\gamma}}{4m^4 m_\rho}. \quad (33)$$

The model coupling constants and masses are :$g_{\pi NN} = 13.14$, $g_{\rho NN} = 1.35$, $g_{\omega NN} = 4.2$, $m_\pi = 136.5MeV$,$m_\rho = 776MeV$, $m_\omega = 782.4MeV$; $g_{\rho\pi\gamma} = 0.52$, $m = 939MeV$. In numerical calculations, the ρ- meson width ($\Gamma_\rho = 154MeV$) has been taken into account by the rule [23], [24]:

$$\frac{m_\rho^2}{m_\rho^2 + t} \to \frac{m_\rho^2 + 8\Gamma_\rho m_\pi/\pi}{m_\rho^2 + t + (t + 4m_\pi^2)\Gamma_\rho \alpha(t)/m_\pi}, \quad (34)$$

$$\alpha(t) = \frac{2}{\pi}\sqrt{\frac{t + 4m_\pi^2}{t}} \ln\{\frac{\sqrt{t + 4m_\pi^2} + \sqrt{t}}{2m_\pi}\}. \quad (35)$$

Tensor polarization of the deuteron can be written as follows

$$T_{20} = -\frac{1}{\sqrt{2}}\frac{1 + X}{1 + \frac{X^2}{8}}, \quad (36)$$

where

$$X = 2\sqrt{2}\frac{F_C}{F_Q}, \quad (37)$$

3 The Results and Discussion

Let us consider the role of individual contributions of the MEC to $F_{C,Q,M}$-form factors. Fig. 1 shows our calculations of the F_C. It is seen that at small momentum scale the contribution of pair current (curve 2) is very important whereas the $\rho\pi\gamma$ current is small (curve 3) and gives a smaller contribution than the retardation effects (curve 4). It is shown that contributions of meson-exchange curents, at small momentum scale, shift the minimum of F_C towards smaller q^2. At the $q^2 > 75\, fm^{-2}$ the retardation effects are negligible and the behaviour of the total charge form factor (curve 5) is determined by competition of pair and $\rho\pi\gamma$ contributions with impulse approximation.

The F_Q- form factor is shown in Fig. 2. At small momentum transfer the contributions of $\rho\pi\gamma$ currents and retardation effects are overshadowed by pair current. At high momentum transfer the main role of pair current is conserved whereas the total contribution of $\rho\pi\gamma$, retardation -currents and impulse approximation is negligible.

The contribution of F_M -form factor is shown in Fig. 3. It is seen that MEC, which are revealed at $q^2 > 40\, fm^{-2}$, shift minimum of the impulse approximation towards high q^2. The competition of pair and $\rho\pi\gamma$ currents with negative impulse approximation determines the behaviour of the total form factor at high momentum transfer and greatly decreases F_M in comparison with the impulse contribution (curve 5). The retardation effects are very small at all momentum scale.

The structure function of the deuteron $A(q^2)$ is shown in Fig.4. It is seen that the contributions of MEC diminish $A(q^2)$ at $80fm^{-2} < q^2 < 150fm^{-2}$, thus making the agreement with experimental data worse (curve 3). One should note the importance of taking account of MEC at $q^2 > 40fm^{-2}$.

The structure function $B(q^2)$ with allowance for MEC is shown in Fig.5. and the calculation without taking account of MEC (curve 1). Comparing the obtained result with the experimental data we get that the MEC effects are very important for the transfer momenta $q^2 > 40fm^{-2}$. The retardation effects (curve 3) are not essential at all momentum scale

The tensor polarization of the deuteron $T_{20}(q^2)$ with allowance for MEC is shown in Fig.6. Data from: Novosibirsk 87 [19], Bates 84 [20], Novosibirsk 90 [21], Bates 90 [22]. It is seen that in comparison with the impulse approximation (curve 1) the contribution of MEC slowly increases $T_{20}(q^2)$ after the minimum. The inclusion of retardation effects does not change the situation.

4 Conclusion

The calculations of the structure functions $A(q^2)$, $B(q^2)$ and tensor polarization $T_{20}(q^2)$ allow one to make the following conclusions:

1. The contributions of meson exchange currents to structure functions $A(q^2)$, $B(q^2)$ at large transfer momenta should be taken into account.
2. The contributions of MEC to $T_{20}(q^2)$ are significant for $q > 2.5fm^{-1}$.
3. The retardation effects are very small for $B(q^2)$ in the whole momentum scale.

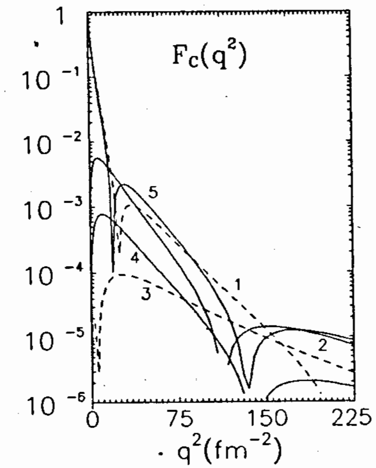

Fig.1: The charge F_C form factor of the deuteron. The dashed line 1 is the impulse approximation; the solid line 2 is the pair current; the dashed line 3 is the $\rho\pi\gamma$-contribution; the solid line 4 is the retardation effects; the solid line 5 is the pair + $\rho\pi\gamma$ + retardation effects

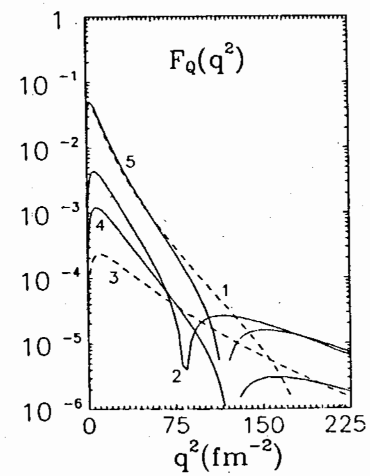

Fig.2: The quadrupole F_Q form factor of the deuteron. Notation is the same as in Fig.1

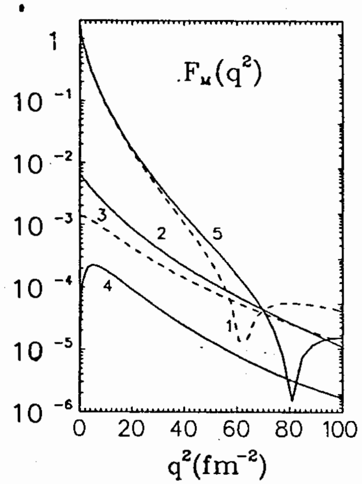

Fig.3: The magnetic F_M form factor of the deuteron. Notation is the same as in Fig.1

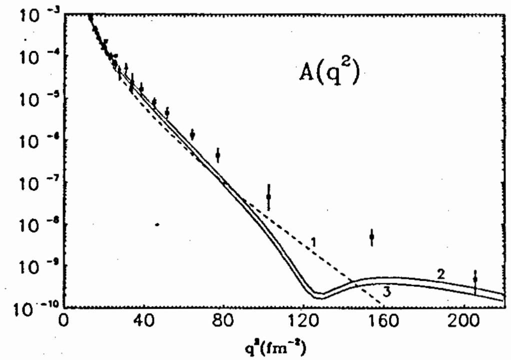

Fig.4: Deuteron structure function $A(q^2)$. The dashed line 1 is the impulse approximation; the solid line 2 is the pair + $\rho\pi\gamma$; solid line 3 is the pair + $\rho\pi\gamma$ + retardation effects

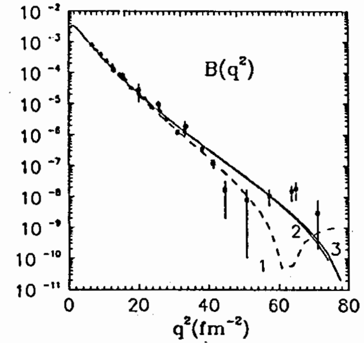

Fig.5: Deuteron structure function $B(q^2)$. Notation is the same as in Fig.4

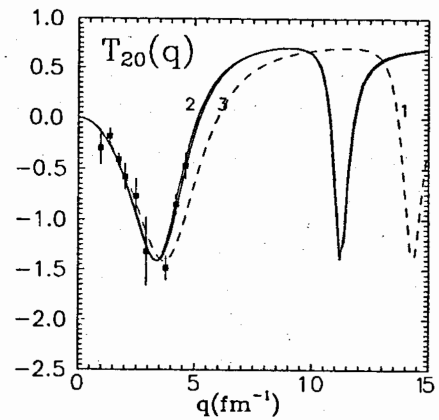

Fig.6: Deuteron tensor polarization $T_{20}(q^2)$. Notation is the same as in Fig.4

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