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MAGNETIC FORM FACTOR OF THE DEUTERON WITH ALLOWANCE FOR MESON EXCHANGE CURRENTS

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1. INTRODUCTION

The available experimental data on the deuteron structure function $B(q^2)$ allow a detailed analysis of elastic eD - scattering within approaches that take account of nonnucleon degrees of freedom in the nucleus. An approach of that sort is the model of meson exchange currents (MEC) that takes account of meson degrees of freedom. The model has been developed by Chemtob and Rho in Ref.[1] where a general classification has been given for the two-particle exchange current. In Ref.[2], the contributions of isoscalar exchange currents to the structure functions $A(q^2)$ and $B(q^2)$ have thoroughly been studied and it has been shown that the contributions of ω - and ρ - mesons may be neglected as compared with the contribution of a more light π - meson. Interaction of a γ - quantum with a meson by which nucleons exchange determines the contribution of $\rho\pi\gamma$ - process (Fig.1). The pair current contribution is shown in Fig.2.

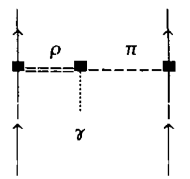

Fig.1. Diagram of the $\rho\pi\gamma$ process.

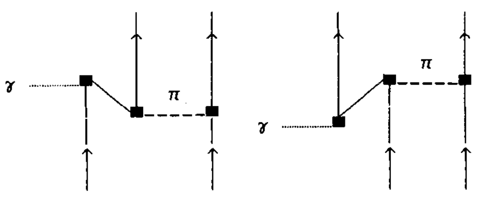

Fig.2. Diagram of pair current.

In Ref.[3], the influence of MEC on the deuteron magnetic form factor has been studied as a function of meson-nucleon form factors. A significant decrease of the deuteron magnetic form factor is predicted when MEC are taken into account in the region $q^2>50$ fm^{-2}. Precision experiments [4] on the study of the structure function $B(q^2)$ have doubled the range of measured transfer momenta, which requires a more correct consideration of MEC with retardation effects included.

The retardation effects have been determined in Refs.[5,6]. In Ref.[5], within the FST method, a general expression has been obtained for the retardation current consisting of the recoil current (RC) and renormalization current (WFR). In Refs.[7,8], expressions for the charge densities of the retardation current ($\rho^{ret,\alpha}$ $\alpha=\pi,\rho,\omega$) have been found and it has been shown that the RC and WFR currents fully compensate for each other in the order $O(1/m^2)$ (m is the nucleon mass). In Ref.[9], expressions have been derived for the spatial component of the retardation current ($j^{ret,\pi}$) in the order $O(1/m^4)$ for the pion exchange and magnetic form factor $F_M^{ret,\pi}$.

It is an task important to use the MEC model for computations of the MEC contributions consistent with a particular choice of the deuteron wave functions and meson-nucleon form factors. In this paper, we calculated the structure function with the use of the phenomenological Paris [10] and Bonn [11] potentials, with allowance made for the impulse approximation F_M^{i} , pair current $F_M^{\pi NN}$, $\rho\pi\gamma$-process $F_M^{\rho\pi\gamma}$, and for the retardation current $F_M^{ret,\pi}$. The structure function $B(q^2)$ was defined in the form $B(q^2)=4\eta(1+\eta)(F_M^{i}+F_M^{\pi NN}+F_M^{\rho\pi\gamma}+F_M^{ret,\pi})^2/3$, where $\eta=q^2/4M^2$ (M is the deuteron mass). The following choice of meson - nucleon form factors were investigated:

1. The Paris potential

$$K_\alpha(k^2) = \frac{1}{(1 + k^2/\Lambda^2_{1,\alpha})\ (1 + k^4/\ \Lambda^4_{2,\alpha})} \qquad (\alpha=\pi NN,\rho NN), \qquad (1)$$

where $\Lambda_{1,\pi NN}=$ 0.99GeV, $\Lambda_{2,\pi NN}=$ 2.58GeV, $\Lambda_{1,\rho NN}=$ 0.77GeV, $\Lambda_{2,\rho NN}=$ 2.58GeV were extracted from the analysis of nucleon form factors. This choice ensures a monopole behaviour at small q^2, which is usually employed in low-energy reactions, and the $(q^2)^{-3}$-dependence at large q^2, which follows from QCD [12]. The coupling constants are as follows: $g_{\pi NN}=13.5$, $g_{\rho NN}=2.56$.

2. The Born potential (full model, relativistic model)

a) Parameterization is taken from Ref.[11]:

$$K_\alpha(k^2) = \left(\frac{\Lambda^2_\alpha - m^2_\alpha}{\Lambda^2_\alpha + k^2}\right)^{n_\alpha}, \qquad (2)$$

m_α is the meson mass, $\Lambda_{\pi NN}=1.3$GeV, $\Lambda_{\rho NN}=$ 1.4GeV, $n_{\pi NN}=n_{\rho NN}=1$ (full model); $\Lambda_{\pi NN}=1.3$GeV, $\Lambda_{\rho NN}=2$GeV, $n_{\pi NN}=1$, $n_{\rho NN}=2$ (relativistic model).

b) Parameterization (1) is used. The coupling constants of the Bonn model are redefined so that the resulting form factor $K_\alpha(k^2)$ be normalized to unity:

$$g_\alpha \to g_\alpha \left(1 - \frac{m^2_\alpha}{\Lambda^2_\alpha}\right)^{n_\alpha}. \qquad (3)$$

The coupling constants are:
$g_{\pi NN}=$ 13.45, $g_{\rho NN}=3.25$ (full model);
$g_{\pi NN}=$ 13.55, $g_{\rho NN}=3.19$ (relativistic model).

2. THE MODEL

The retardation current for pion exchange was computed within the FST method on the basis of the time-ordered perturbation theory [13]. Expression for the retardation current was derived from the S-matrix of the process (Fig.3):

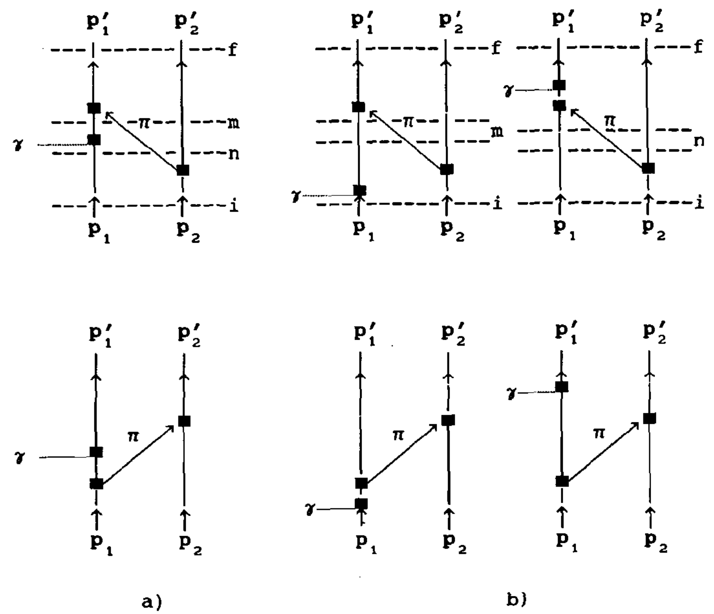

Fig.3. Diagram of retardation current:a) RC - current b) WFR -current.

$$S_{fi}= -2\pi i\delta(E_1' + E_2' - E_1 - E_2 - q_0)(\chi_f|H^{ret}|\chi_i), \qquad (4)$$

where χ is the wave function of a nucleon state, H^{ret} is the interaction operator defining the retardation effects in meson exchange currents. The matrix element of interaction is connected with the retardation current as follows:

$$(\chi_f|H^{ret}|\chi_i)=\frac{\delta(\mathbf{p}_1'+\mathbf{p}_2'-\mathbf{p}_1-\mathbf{p}_2-\mathbf{q})}{(2\pi)^3}\, j_\mu^{ret}V^\mu \tag{5}$$

(q_0 and $\mathbf{q}$ are, resp., the energy and momentum of a γ-quantum). Introducing the initial- and final-state vectors, $\phi_i=b^+(\mathbf{p}_1)b^+(\mathbf{p}_2)\phi_0$ and $\phi_f=b^+(\mathbf{p}_1')b^+(\mathbf{p}_2')\phi_0$, where $b^+(\mathbf{p})$ is the operator of creation of a nucleon with momentum $\mathbf{p}$, ϕ_0 is the nucleon vacuum, we obtain for the matrix element (5) the following expression:

$$(\chi_f|H^{ret}|\chi_i)=(\phi_f,H_\pi\frac{1}{E_f-H_0}\Lambda_m H_A\frac{1}{E_i-H_0}\Lambda_n H_\pi\phi_i)-$$
$$\frac{1}{2}\{(\phi_f,H_\pi\frac{1}{(E_f-H_0)(E_i-H_0)}\Lambda_m H_\pi H_A\phi_i)+(\phi_f,H_A H_\pi\frac{1}{(E_f-H_0)(E_i-H_0)}\Lambda_n H_\pi\phi_i)\}. \tag{6}$$

Here [5] Λ_m and Λ_n are the projection operators on meson-nucleon states m and n. The Hamiltonians of strong, H_π, and electromagnetic, H_A, interaction are of the form

$$H_\pi=g\int dx\,\bar{\Psi}(x)\gamma_5\Psi(x)(\vec{\tau}\cdot\vec{\pi}(x)),$$
$$H_A=e\int dx\,\bar{\Psi}(x)\gamma_\mu\Psi(x)A^\mu(x), \tag{7}$$

where g, and e are strong and electromagnetic coupling constants, resp.; $\Psi(\mathbf{x})$ and $\pi(\mathbf{x})$ are nucleon and meson field operators. Choosing the Breit system where $q_0=0$, we take the electromagnetic field to be a plane monochromatic wave

$$A^\mu(\mathbf{x})=V^\mu(\mathbf{q})e^{i\mathbf{qx}} \tag{8}$$

In view of the strong and electromagnetic interactions being nonlocal we should make the following changes: for the electromagnetic field,

$$\gamma_\mu\to\Gamma_\mu=\frac{1}{2}F_1^S\gamma_\mu+\frac{i}{4m}F_2^S\sigma_{\mu\nu}q^\nu \tag{9}$$

and for the strong interaction,

$$g\to g_{\pi NN}K_{\pi NN}(k^2). \tag{10}$$

Here F_1^S and F_2^S are isoscalar electromagnetic form factors of a nucleon; $K_{\pi NN}(k^2)$ is a pion-nucleon interaction form factor. We insert (7)-(10) into (6) and pass to the nonrelativistic limit for current matrix elements (see also Ref.[14])

$$\bar{\omega}(\mathbf{p}')\gamma_5\omega(\mathbf{p})\to-\frac{i\vec{\sigma}(\mathbf{p}-\mathbf{p}')}{2m},$$
$$\bar{\omega}(\mathbf{p}')\vec{\Gamma}\omega(\mathbf{p})\to\frac{1}{2}\{\frac{F_1^S}{2m}(\mathbf{p}'+\mathbf{p})+\frac{iG_N^S(\vec{\sigma}\times\mathbf{q})}{2m}\}, \tag{11}$$

where $\omega(\mathbf{p})$ is the Dirac spinor ($\bar{\omega}(\mathbf{p})\omega(\mathbf{p})=1$), $G_N^S=F_1^S+F_2^S$, $\mathbf{q}=\mathbf{p}'-\mathbf{p}$. Then, using definitions (4), (5) we obtain the following expression for the retardation current (Fig.3):

$$j^{ret,\pi}=j_a^{ret,\pi}+j_b^{ret,\pi}+(1\leftrightarrow2), \tag{12}$$

where separate contributions are given by

$$j_a^{ret,\pi}=-i\frac{G_N^S}{8m^2}(\frac{g_{\pi NN}}{2m})^2(\vec{\tau}_1\cdot\vec{\tau}_2)(\mathbf{k}_2\times\mathbf{q})(\mathbf{q}\cdot\mathbf{k}_2)(\vec{\sigma}_2\cdot\mathbf{k}_2)\frac{K_{\pi NN}^2(k_2^2)}{(k_2^2+m_\pi)^2} \tag{12.a}$$

$$j_b^{ret,\pi}=\frac{1}{8m^2}(\frac{g_{\pi NN}}{2m})^2(\vec{\tau}_1\cdot\vec{\tau}_2)\{G_N^S(\mathbf{k}_2(\mathbf{q}\cdot\mathbf{k}_2)(\vec{\sigma}_1\cdot\mathbf{q})(\vec{\sigma}_2\cdot\mathbf{k}_2)-$$
$$\vec{\sigma}_1(\mathbf{q}\cdot\mathbf{k}_2)^2(\vec{\sigma}_2\cdot\mathbf{k}_2))-F_1^S\mathbf{k}_2(\mathbf{q}\cdot\mathbf{k}_2)(\vec{\sigma}_1\cdot\mathbf{k}_2)(\vec{\sigma}_2\cdot\mathbf{k}_2)\}\frac{K_{\pi NN}^2(k_2^2)}{(k_2^2+m_\pi^2)^2} \tag{12.b}$$

$$\mathbf{k}_2=\mathbf{p}_2'-\mathbf{p}_2.$$

It is to be noted that the current was obtained through expanding in the inverse mass of a nucleon 1/m. Therefore it is natural to assume that the region of influence of MEC is restricted to the transfer momenta q<1GeV. However, as will be seen later, the main contribution to the magnetic form factor comes from MEC in the range of q/2. As we think, this allows us to extend the range of applicability of the approach up to q<2GeV.

3. FORM FACTORS

The magnetic form factor of the deuteron is of the form

$$F_M(q^2)=-\langle D|\frac{3im}{2\pi q^2}\int\frac{d\mathbf{k}}{(2\pi)^3}\int d\Omega_q\, e^{i(\mathbf{qr}/2-\mathbf{kr})}(\mathbf{q}\times\mathbf{j}(\mathbf{k},\mathbf{q}))_0|D\rangle, \tag{13}$$

where $|D\rangle$ is the deuteron wave function, $j(\mathbf{k},\mathbf{q})$ is the current of a given process; $\mathbf{r}=\mathbf{r}_1-\mathbf{r}_2$ ($\mathbf{r}_1$ and $\mathbf{r}_2$ are spatial coordinates of nucleons). Inserting $j^{ret,\pi}(\mathbf{k}_2,\mathbf{q})$ into (13) and performing some algebra, we get for the retardation form factor

$$F_M^{ret,\pi} = \frac{9}{5}\, q\, (\frac{1}{m})^3 (\frac{g_{\pi NN}}{4\pi})^2\, G_M^S \int_0^\infty dr\, (j_1(qr/2)A_1(r) + j_3(qr/2)A_2(r)),$$

$$A_1(r) = 2/3\, U^2(r)\, I_1(r) + 1/5\, (\sqrt{2}\, U(r)W(r)\, (1/3\, I_1(r) - 3\, I_3(r)) - W^2(r)\, (4/3\, I_1(r) + 3\, I_3(r))), \qquad (14)$$

$$A_2(r) = -2/3\, U^2(r)\, I_3(r) + 1/5\, (\sqrt{2}\, U(r)W(r)\, (2\, I_1(r) - 4/3\, I_3(r)) + W^2(r)\, (2\, I_1(r) + 1/3\, I_3(r)));$$

$$I_1(r) = \int_0^\infty dk\, k^5\, j_1(kr)\, \frac{K_{\pi NN}^2(k^2)}{(k^2+m_\pi^2)^2}, \qquad (14.a)$$

$$I_3(r) = \int_0^\infty dk\, k^5\, j_3(kr)\, \frac{K_{\pi NN}^2(k^2)}{(k^2+m_\pi^2)^2}. \qquad (14.b)$$

Here $j_{1(3)}(kr)$ is the spherical Bessel function. It is interesting that the contribution of current $j_b^{ret,\pi}$ into $F_M^{ret,\pi}$ is zero. The form factors for impulse approximation, πNN- and $\rho\pi\gamma$- processes have been determined in Refs.[2,3] and are of the form

$$F_M^i = \frac{3}{2} G_E^S\, (I_{22}^0(q/2) + I_{22}^2(q/2)) + 2\, G_M^S\, (I_{00}^0(q/2) - \frac{1}{2} I_{22}^0(q/2) + \frac{1}{\sqrt{2}} I_{20}^2(q/2) + \frac{1}{2} I_{22}^2(q/2)). \qquad (15)$$

$$F_M^{\pi NN} = \frac{g_{\pi NN}^2}{8m^3\pi^2} G_M^S \int_0^\infty dk\, k^2\, (k^2\, (J_0^\pi - J_2^\pi)\, (I_{00}^0(k) - \frac{1}{2} I_{22}^0(k)) - (k^2\, (J_0^\pi - J_2^\pi) + \frac{9}{20} kq\, (J_1^\pi - J_3^\pi))\, (\sqrt{2}\, I_{20}^2(k) + I_{22}^2(k))). \qquad (16)$$

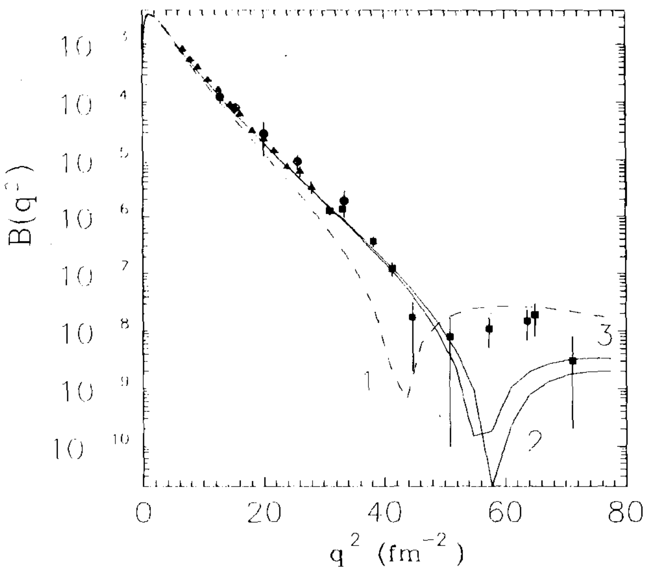

Fig. 4. Deuteron structure function B(q). The dashed line **1** is the impulse approximation with the Paris wave functions, the solid line **2** with inclusion of MEC (πNN + $\rho\pi\gamma$) and the solid line **3** with inclusion of MEC (πNN + $\rho\pi\gamma$ + retardation effects). The experimental data are taken from [4].

The contribution of $\rho\pi\gamma$-process can be found from (16) with the change

$$\frac{g_{\pi NN}^2 G_M^S}{8m^3} \to \frac{g_{\pi NN} g_{\rho NN} g_{\rho\pi\gamma}}{m_\rho} K_{\rho\pi\gamma}, \quad J_1^\pi \to J_1^{\rho\pi\gamma}. \qquad (17)$$

$$I_{00}^1(k) = \int_0^\infty dr\, U^2(r)\, j_1(kr), \qquad I_{22}^1(k) = \int_0^\infty dr\, W^2(r)\, j_1(kr), \qquad (18)$$

$$I_{20}^1(k) = \int_0^\infty dr\, U(r)\, W(r)\, j_1(kr).$$

U(r) and W(r) are wave functions of deuteron S- and D- waves.

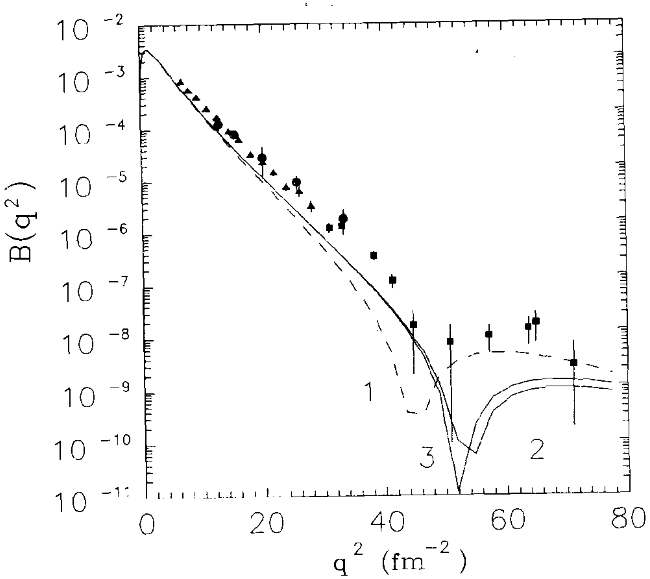

Fig.5. Deuteron structure function B(q). The calculations are made with Bonn wave functions (full model) and parameterization (2). Notation is the same as Fig.4.

$$J_1^{\pi} = \int_{-1}^{1} P_1(x) \frac{K_{\pi NN}(k^2 + q^2/4 + qkx)^2}{m_\pi^2 + k^2 + q^2/4 + qkx} dx \;, \qquad (19)$$

$$J_1^{\rho\pi\gamma} = \int_{-1}^{1} P_1(x) \frac{K_{\rho NN}(k^2 + q^2/4 - qkx)}{(k^2 + q^2/4 - qkx + m_\rho^2)} \frac{K_{\pi NN}(k^2 + q^2/4 + qkx)}{(k^2 + q^2/4 + qkx + m_\pi^2)} dx. \qquad (20)$$

G_M^s is the isoscalar magnetic form factor, and [2]

$$G_E^S = \frac{G_M^S}{1+k_S} = (1 + \frac{q^2}{0.71GeV^2})^{-2}, \; k_S = -0.12; \qquad (21)$$

$$K_{\rho\pi\gamma} = (1 + \frac{q^2}{m_\omega^2})^{-1}, \qquad (22)$$

$$C_{\rho\pi\gamma} = -\frac{g_{\rho NN} g_{\pi NN} g_{\rho\pi\gamma}}{4m^2 m_\rho} (1+k_V), \; k_V = 3.71; \; g_{\rho\pi\gamma} = 0.52 \; [15]. \qquad (23)$$

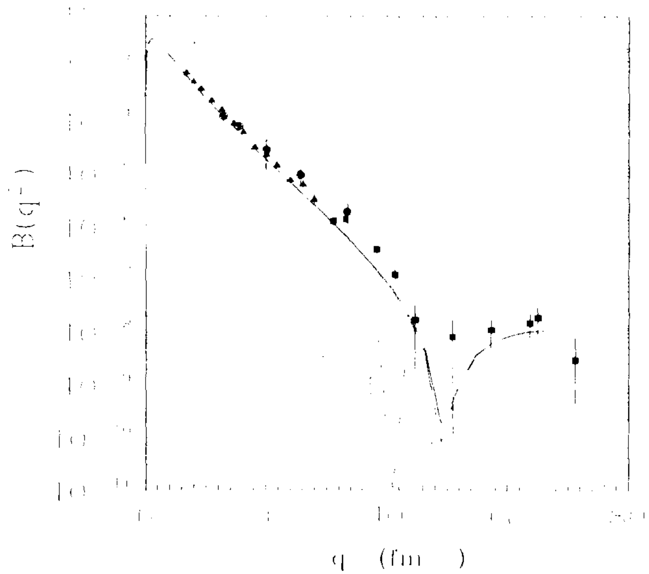

Fig.6. Deuteron structure function B(q). The calculations are made with Bonn wave functions (relativistic model) and parameterization (2). Notation is the same as Fig.4.

In numerical calculations, the ρ-meson width (Γ_ρ 154MeV) has been taken into account by the rule [16, 17]:

$$\frac{m_\rho^2}{m_\rho^2 + t} \;,\; \frac{m_\rho^2 + 8\Gamma_\rho m_\pi/\pi}{m_\rho^2 + t + (4m_\pi^2 + t)\,\Gamma_\rho \alpha(t)/m_\pi} \;, \qquad (24)$$

$$\alpha(t) = \frac{2}{\pi} \left(\frac{t + 4m_\pi^2}{t}\right)^{1/2} \ln\left(\frac{(t + 4m_\pi^2)^{1/2} + t^{1/2}}{2m_\pi}\right), \qquad (25)$$

4. RESULTS AND DISCUSSION

Calculation of the structure function $B(q^2)$ with the use of wave functions of the Bonn potential and inclusion of pair πNN- and $\rho\pi\gamma$- processes was given in Ref. [9]. Here we consider the retardation effects influence. From Fig.4 it is seen that in case of the Paris potential in the region of $q^2 < 42 fm^{-2}$ the retardation effects are negligible. In the range of large q^2 the retardation effects produce a rise and a shift of the minimum of the structure function

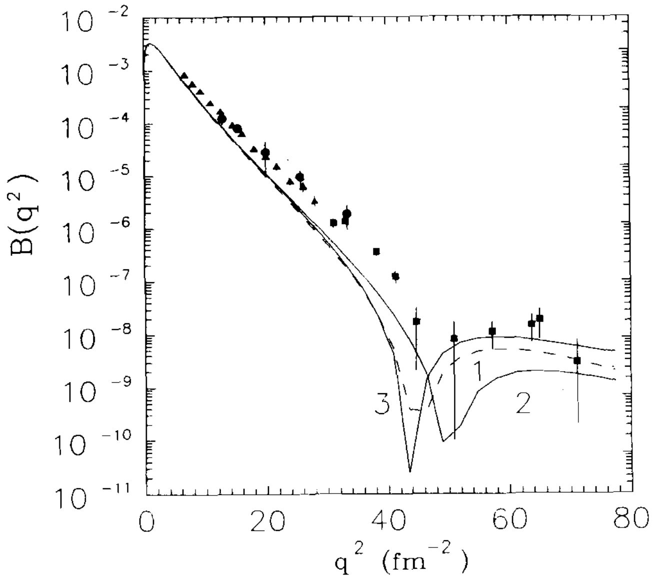

Fig.7. Deuteron structure function B(q). The calculations are made with Bonn wave functions (full model) and parameterization (3). Notation is the same as Fig.4.

towards smaller transfer momenta but does not improve the agreement with experiment.

In Fig.5 we present the calculations made with the Bonn wave functions (full model) and with parameterization (2). As it is seen the retardation effects are negligible in the range of $q^2<46fm^{-2}$. Also,a decrease of the structure function $B(q^2)$ is observed in the minimum and its shift towards smaller q^2. In the region of large transfer momenta, $q^2>50fm^{-2}$, the retardation effects influence on the structure function is insignificant. In case of the Bonn relativistic model, the retardation effects produce a slight influence on the structure function (Fig.6). The retardation effects are more manifest in the calculations with variant (3). From Fig.7 it is seen that the retardation effects are significant even at $q^2>30fm^{-2}$ (full model). In the range $42<q^2<49fm^{-2}$ a significant shift occurs in the minimum of the structure function $B(q^2)$ towards smaller transfer momenta. In the range $q^2>46fm^{-2}$, $B(q^2)$ undergoes a considerable rise, crossing experimental points. In case of the relativistic model, the retardation effects being taken into account worsen the agreement with experiment, especially in the region $50<q^2<66fm^{-2}$ (Fig.8).

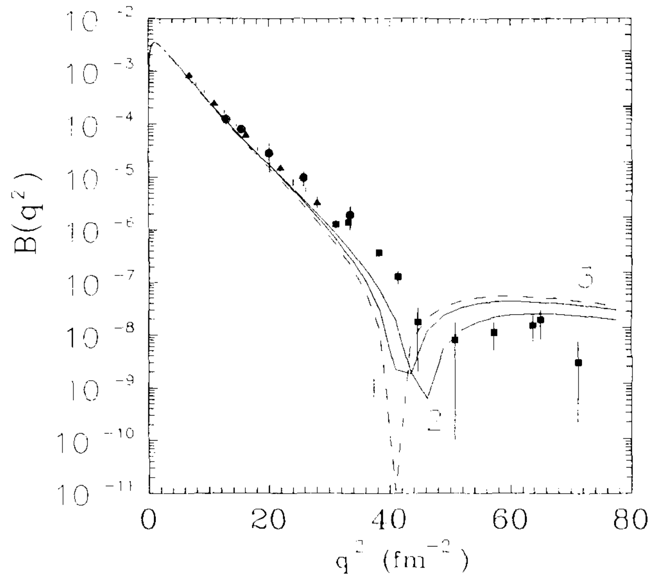

Fig.8. Deuteron structure function B(q). The calculations are made with Bonn wave functions (relativistic model) and parameterization (3). Notation is the same as Fig.4.

Thus, we may conclude as follows:

The retardation effects in meson exchange current play a very important role. For instance, in the cases plotted in Figs. 7 and 8 the contribution of retardation effects almost completely compensates the contributions of πNN- and $\rho\pi\gamma$-currents thus much diminishing the total contribution of MEC to $B(q^2)$.

The retardation effects are very sensitive to the choice of meson-nucleon form factors being the most significant at large transfer momenta.

The considered choice of the phenomenological and exact nucleon-nucleon potentials does not much affect the magnitude of the contribution of retardation effects to MEC.

Generally speaking, the calculation of the structure function $B(q^2)$ with retardation effects included into consideration does not allow us to improve the agreement with experiment at large transfer momenta where probably other degrees of freedom are to be taken into account.

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Магнитный формфактор дейтрона
с учетом мезонных обменных токов

Исследовано влияние эффектов запаздывания на магнитный формфактор дейтрона в зависимости от выбора мезон-нуклонных формфакторов и дейтронных волновых функций. Продемонстрирована необходимость учета эффектов запаздывания в МОТ. Показано, что вклад эффектов запаздывания сильно зависит от мезон-нуклонных формфакторов в области больших переданных импульсов. Рассматриваемый выбор волновых функций Парижского и Боннского потенциалов не оказывает заметного влияния на характер проявления эффектов. Для структурной функции $B(q^2)$ получено, что учет МОТ, включая эффекты запаздывания, не позволяет улучшить согласие с экспериментом при больших переданных импульсах.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Magnetic Form Factor of the Deuteron
with Allowance for Meson Exchange Currents

The retardation effects on the deuteron magnetic form factor have been studied on the choice of meson-nucleon form factors and deuteron wave functions. It is shown that the retardation effects should be taken into account in MEC. The contribution of retardation effects is proved to be strongly dependent on meson-nucleon form factors at large transfer momenta. The considered set of wave functions of the Paris and Bonn potential does not much influence the way, these effects manifest themselves. It is found for the structure function $B(q^2)$ that inclusion of MEC and the retardation effects does not improve the agreement with experiment at large transfer momenta.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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