Meson exchange currents and the magnetic form factor of the deuteron

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The effect of meson exchange currents on the magnetic form factor of the deuteron is studied. The meson exchange currents depend strongly on the meson-nucleon form factors. The structure function $B(q^2)$ is found to be in agreement with the experiment over the entire range of measured momentum transfer, $q^2 \leqslant 28\ \mathrm{fm}^{-2}$, if the meson-nucleon form factors are chosen in accordance with the quantum-chromodynamics rules. The magnetic form factor of the deuteron is predicted to decrease appreciably if the meson exchange currents are taken into account in the range of momentum transfer $q^2 > 50\ \mathrm{fm}^{-2}$.

The recent precision experiments[1] in which the deuteron structure function $B(q^2)$ was studied have broadened the range of measured momentum transfer by a factor of two. Analysis of the theoretical situation shows that the experimental structure function $B(q^2)$ cannot be described either in terms of the nonrelativistic approach based on various nucleon-nucleon potentials or by taking the relativistic effects in the deuteron into account.[2,3] The effective nucleon-nucleon potentials upon which the nonrelativistic description of the deuteron is based are the consquence of the meson exchange: For this reason, in a certain range of momentum transfer the meson degrees of freedom should manifest themselves in the elastic scattering of electrons by a deuteron. The isoscalar meson exchange currents were studied particularly thoroughly by Gari and Hyuga,[4] who showed that the pairing-current diagrams and the $\rho\pi\gamma$ process, which determine the meson exchange currents, are highly sensitive to the meson-nucleon form factors. Burov *et al.*[5] revised the meson exchange currents on the basis of the meson-nucleon form factors which were constructed in such a way that at small momentum transfer the low-energy data on the $NN \to NN\pi$ reactions could be reporduced and at large momentum transfer their behavior would be determined by the quantum-chromodynamics rules. Burov *et al.*[5] were able to describe the structure function $A(q^2)$ to within a momentum transfer $q^2 < 75\ \mathrm{fm}^{-2}$. Since the structure function $B(q^2)$ is determined by only the magnetic form factor of the deuteron, $F_M(q^2)$, the meson degrees of freedom should manifest themselves in this case in a more striking way. Taking the meson exchange currents into account, the magnetic form factor of the deuteron can be written

$$F_M(q^2) = F_M^{imp}(q^2) + F_M^{\pi NN}(q^2) + F_M^{\rho\pi\gamma}(q^2), \tag{1}$$

where $F_M^{\pi NN}(F_M^{\rho\pi\gamma})$ corresponds to the pairing-current contribution (the $\rho\pi\gamma$ process).[4] The structure function $B(q^2)$ is defined by the expression $B(q^2) = (4/3)\eta(1+\eta)F_M^2(q^2)$, where $\eta = q^2/4M_d^2$. The correction to the pairing current is

$$F_M(q^2) = -\frac{1}{\pi^2}\frac{g^2_{\pi NN}G^S_M(q^2)}{8m^3_N}\int_0^\infty dkk^2\Big\{k^2(J^\pi_0 - J^\pi_2)(I^0_{00}(k) - \frac{1}{2}I^0_{22}(k))$$

$$-\left[k^2(J^\pi_0 - J^\pi_2) + \frac{9}{20}kq(J^\pi_1 - J^\pi_3)\right](\sqrt{2}I^2_{20}(k) + I^2_{22}(k))\Big\}. \qquad (2)$$

In expression (2) the deuteron structure is given by the functions

$$I^l_{mn}(k) = \int_0^\infty u_m(r)u_n(r)j_l(kr)dr, \qquad (3)$$

where $u_0 \equiv u(r)$ and $u_2 \equiv w(r)$ are, respectively, the S and D waves of the deuteron. The functions J^π_l depend on the meson-nucleon form factors and define the momentum-transfer region in which the pairing current must be taken into account,

$$J^\pi_l(k, q) = \int_{-1}^{1} P_l(x)\frac{K^2_{\pi NN}(k^2 + q^2/4 + qkx)}{k^2 + q^2/4 + qkx + m^2_\pi}dx . \qquad (4)$$

The contribution to the pairing current from the exchange of heavier mesons is considerably smaller than that from the π meson.[4] The expression for the contribution from the $\rho\pi\gamma$ process can be found from (2) through the substitution

$$\frac{g^2_{\pi NN}G^S_M}{8m^3_N} \rightarrow \frac{g_{\pi NN}g_{\rho NN}g_{\rho\pi\gamma}}{m_\rho}K_{\rho\pi\gamma}, \quad J^\pi_l \rightarrow J^{\rho\pi\gamma}_l,$$

where $K_{\rho\pi\gamma}$ is determined in the vector-dominance model. The functions $J^{\rho\pi\gamma}_l$ regulate the range in which the $\rho\pi\gamma$ process contributes:

$$J^{\rho\pi\gamma}_l(k, q) = \int_{-1}^{1} P_l(x)\frac{K_{\pi NN}(k^2 + q^2/4 + qkx)K_{\rho NN}(k^2 + q^2/4 - qkx)}{(k^2 + q^2/4 + qkx + m^2_\pi)(k^2 + q^2/4 - qkx + m^2_\rho)}dx. \qquad (5)$$

The following parametrization is used for the meson-nucleon form factors[6] $K_{\pi NN}$ and $K_{\rho NN}$:

$$K_\alpha(q^2) = 1/[(1 + q^2/\lambda^2_{1,\alpha})(1 + q^4/\lambda^4_{1,\alpha})], \qquad (\alpha \equiv \pi NN, \quad \rho NN) . \qquad (6)$$

The parameter values are $\lambda_{1,\pi NN} = 0.99$ GeV/c, $\lambda_{2,\pi NN} = 2.58$ GeV/c, $\lambda_{1,\rho NN} = 0.77$ GeV/c, and $\lambda_{2,\rho NN} = \lambda_{2,\pi NN}$. Such a choice of the meson-nucleon form factors assures that $K_\alpha(q^2) \sim (q^2)^{-3}$ will apply at large momentum transfer, which is prescribed by quantum chromodynamics.[6]

It should be pointed out that the meson exchange currents are found by using the expansion in the reciprocal of the nucleon mass $1/m_N$. It is therefore logical to assume that the effective range of the meson exchange currents is restricted by the momentum transfer[7] $q < 1$ GeV/c. Expressions (4) and (5) show, however, that the meson exchange currents contribute to the magnetic form factor primarily at $q/2$. This circumstance makes it possible, in our view, to expand the range of applicability of this approach to $q \lesssim 2$ GeV/c if the meson exchange currents are taken into account.

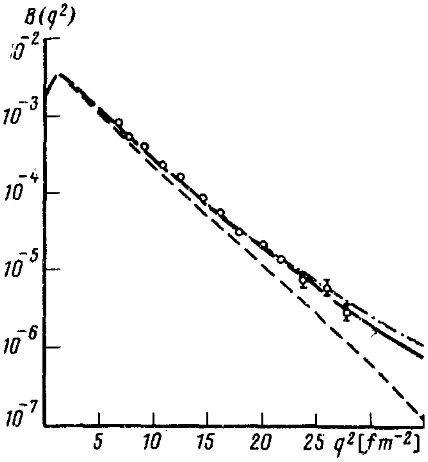

FIG. 1. The structure function $B(q^2)$. Dashed line—impulse approximation; solid line—with allowance for the meson exchange currents; dot-dashed line—with allowance for the meson-exchange currents with the meson-nucleon form factors obtained in Ref. 4. The experimental data points were taken from Ref. 1.

The numerical calculations were carried out with use of the "Paris" wave functions.[8] The ρ-meson width, $\Gamma_\rho = 154$ MeV, was taken into account and the constant $g_{\rho\pi\gamma} = 0.52$ was used in the $\rho\pi\gamma$ contribution.[5] Figure 1 shows that the structure function $B(q^2)$ is described well if the meson exchange currents are taken into account for the entire range of measured momentum transfer.[1] As we can see from Fig. 2, the meson-exchange-current corrections raise the theoretical curve in the range of momentum transfer $q^2 < 50$ fm^{-2}, whereas at large momentum transfer the meson exchange currents decrease $B(q^2)$ appreciably in comparison with the impulse approximation (the solid and dashed curves in Fig. 2). Figure 2 also shows the structure function $B(q^2)$ calculated with allowance for the meson exchange currents and the meson-

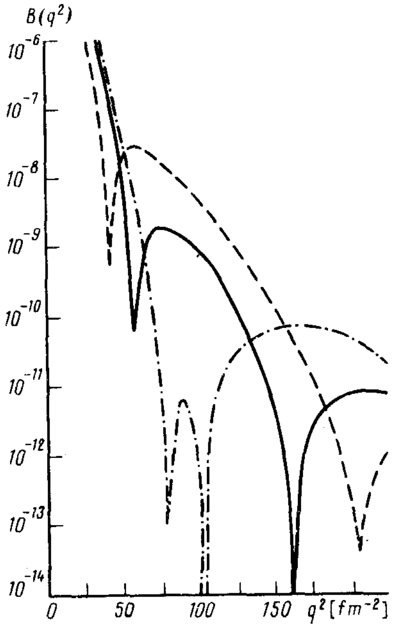

FIG. 2. The structure function $B(q^2)$. The notation is the same as in Fig. 1.

nucleon form factors from Ref. 4 in order to demonstrate the strong sensitivity of the deuteron magnetic form factor to the meson-nucleon form factor at $q^2 > 50\ \text{fm}^{-2}$. The measurement of the structure function $B(q^2)$ in this range of momentum transfer is now being planned at SLAC.[9]

In conclusion, we wish to stress again that the meson degrees of freedom in the deuteron decrease the magnetic form factor appreciably at $q^2 > 50\ \text{fm}^{-2}$.

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