Is the Structure in the Deuteron Magnetic Form Factor at $Q^2 \approx 2$ GeV^2 New Evidence for Nuclear Core?

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(Received 1 August 1988; revised manuscript received 18 November 1988)

Using the relativistic light-cone description of the two-nucleon system we argue that experimental confirmation of the recently observed structure in the deuteron magnetic form factor at $Q^2 \approx 2$ (GeV/c)^2 would provide new independent evidence in favor of the dominant role of nucleonic degrees of freedom in the deuteron.

PACS numbers: 25.30.Bf, 21.30.+y, 25.10.+s, 27.10.+h

Recently the American University–SLAC group has measured the Q^2 dependence of the function $B(Q^2)$ for *ed* elastic scattering up to $Q^2 \approx 2.5$ (GeV/c)^2.[1] Indications were found that $B(Q^2)$ has a zero around $Q^2 \approx 2$ (GeV/c)^2.[1] The oscillating behavior of $B(Q^2)$, if confirmed, can help in distinguishing between several options: dominance of nucleonic degrees of freedom or quark effects at large Q^2, perturbative QCD predictions or light-cone quantum mechanics (LCQM) of the deuteron, etc. The aim of this Letter is to confront these new data with a number of different hypotheses on the high-momentum component of the deuteron wave function (WF).

In the nonrelativistic approach all realistic *NN* potentials with nuclear core predict the oscillating behavior of $\psi_S(k)$ and $\psi_D(k)$,[2] which in turn leads to oscillating behavior of all deuteron form factors $F_{\text{ch}}(Q^2)$, $F_{\text{mag}}(Q^2)$, and $F_Q(Q^2)$. However, the zeros of $F_{\text{ch}}(Q^2)$ and $F_Q(Q^2)$ are at very different Q^2. As a result they cannot be observed in the Q^2 dependence of $A(Q^2)$. On the contrary, the zero of $F_{\text{mag}}(Q^2)$ near $Q^2 \approx 1.5$–2 (GeV/c)^2 gives a very sharp minimum in the function $B(Q^2)$. Besides, the theoretical description of $B(Q^2)$ is mainly determined by the high-Q^2 behavior of $G_{Mp}(Q^2)$ and $G_{Mn}(Q^2)$, which are much better known than $G_{Ep}(Q^2)$ and $G_{En}(Q^2)$, which dominate in $A(Q^2)$.

In the nonrelativistic approach the zero in $B(Q^2)$ is predicted at somewhat lower Q^2 [$Q^2 = 1.5$–1.6 (GeV/c)^2] than observed experimentally. Moreover, the validity of the nonrelativistic approach at such large Q^2 is questionable. Here we calculate $F_{\text{mag}}(Q^2)$ using LCQM of the deuteron. This approach was discussed in detail in Refs. 3 and 4, where all three form factors of the deuteron were calculated. Recently it was also applied to the analysis of the electromagnetic properties of the deuteron in Ref. 5 with similar results.

LCQM is a form of relativistic Hamiltonian quantum dynamics, applied to systems with a fixed number of particles. As compared to quantum field theory it should be considered as an approximate description of a physical system where only a limited number of degrees of freedom is taken into account (see, e.g., Refs. 3–6). Experimentally $^3S_1, ^3D_1$ $I=0$ *NN* phase shifts are practically elastic up to $T_p \approx 1$ GeV (this fact is not explained as yet by one-boson-exchange potential models). Thus it seems reasonable as a first approximation to neglect non-nucleon degrees of freedom in the dynamics of the two-nucleon system, which is governed in this case by the two-body relativistic equation[3(b),6]

$$(\mathbf{k}^2 + m\epsilon_d)\psi(\mathbf{k}) = \int V(\mathbf{k},\mathbf{k}')\frac{d^3k'}{E_{\mathbf{k}'}}\psi(\mathbf{k}') . \qquad (1)$$

(For brevity we neglect nucleon spins here.) The form of this equation is very similar to the nonrelativistic one. So in this approximation the light-cone wave functions of the deuteron may be related to nonrelativistic ones,

$$\psi_{\text{rel}}(\mathbf{k}) = \sqrt{E_{\mathbf{k}}}\,\psi_{\text{nonrel}}(\mathbf{k}) , \qquad (2)$$

where $E_{\mathbf{k}} = (\mathbf{k}^2 + m^2)^{1/2}$ [see also Refs. 3(b) and 6]. A direct construction of $\psi_{\text{rel}}(\mathbf{k})$ and $V(\mathbf{k},\mathbf{k}')$ determined from the *NN* phase-shift analysis is another possibility.

In the framework of relativistic Hamiltonian quantum dynamics, the choice of Eq. (1) corresponds to the specific representation of the two-body Poincaré generators (see Ref. 6). It can be justified in the ladder approximation for the *NN* scattering amplitude in the infinite-momentum frame if the violations of rotation symmetry in the one-boson-exchange potential are small (see, e.g., Ref. 7). They are likely to be small in the partial waves considered because the two-nucleon sector almost saturates the unitarity condition for the $^3S_1$-$^3D_1$ *NN* scattering amplitude at $T_p \lesssim 1$ GeV.[8]

The choice of the current operator in LCQM should also be consistent with the dynamics. The minimal dynamical restrictions are imposed on the "good" component of the electromagnetic current j_+ (see, e.g., Refs. 3–5). Therefore, it is preferable to express the form factors through the matrix elements of the electromagnetic current. In this case, for example, the couplings with other sectors are expected to be minimal because the contribution of $N\bar{N}$ pairs (*Z* diagrams) is maximally suppressed. Moreover, the suppression of Z diagrams is complete for the transverse deuteron polarizations.[3,4] Therefore we calculate the form factors using the matrix elements $\mathcal{J}_{+}^{\lambda'\lambda} = {}_F\langle d'\lambda' \,|\, j_+(0) \,|\, d\lambda\rangle_F$ for $\lambda' = \pm 1$ and $\lambda = \pm 1$ and 0. The expression for the magnetic form factor through the S- and D-wave functions $u(\mathbf{k})$ and $w(\mathbf{k})$ is

$$F_{\text{mag}}(Q^2) = \frac{2}{(1+\eta)^{1/2}} \left[\mathcal{J}_{+}^{+1,+1}(Q^2) - \frac{1}{(2\eta)^{1/2}} \mathcal{J}_{+}^{+1,0}(Q^2) \right], \tag{3}$$

where

$$\mathcal{J}_{+}^{\lambda',\lambda}(Q^2) = {}_F\langle d'\lambda' \,|\, j_+(Q_+ = 0, \mathbf{Q}_\perp) \,|\, d\lambda\rangle_F = \int \frac{d^3k}{2E_{\mathbf{k}}} \mathrm{Sp} \left[\psi_{\lambda'}(\mathbf{k}') \left[F_1^s(Q_\perp^2)\hat{H} - \frac{1}{2m} F_2^s(Q_\perp^2)\hat{G} \right] \psi_\lambda(\mathbf{k}) \hat{\overline{H}} \right],$$

$$\psi_\lambda(\mathbf{k}) = u(\mathbf{k})\sigma_\lambda - \frac{1}{\sqrt{2}} \left[\sigma_\lambda - \frac{3k_\lambda \boldsymbol{\sigma}\cdot\mathbf{k}}{\mathbf{k}^2} \right] w(\mathbf{k}),$$

$$H = U(\tilde{p}')U^\dagger(\tilde{p}), \quad G = U(\tilde{p}')(i\mathbf{Q}_\perp \cdot \boldsymbol{\epsilon} \cdot \boldsymbol{\sigma})U^\dagger(\tilde{p}), \quad \overline{H} = \sigma_y [U(\tilde{n}')U^\dagger(\tilde{n})]^T \sigma_y,$$

$$U(\tilde{p}) \equiv U(\mathbf{k}_\perp, k_3) \equiv \frac{m + E_{\mathbf{k}} + k_3 + i\epsilon_{js}\sigma_j k_{\perp s}}{[2(E_{\mathbf{k}}+m)(E_{\mathbf{k}}+k_3)]^{1/2}},$$

$$U(\tilde{n}) \equiv U(-\mathbf{k}_\perp, -k_3), \quad \mathbf{k}'_\perp = \mathbf{k}_\perp + (1-\alpha)\mathbf{Q}_\perp, \quad \alpha = \frac{E_{\mathbf{k}} + k_3}{2E_{\mathbf{k}}}.$$

This formula takes into account the recoil and spin-rotation effects and corresponds to the graph of Fig. 1(a) calculated in the infinite-momentum frame (see Refs. 3 and 4).

In Fig. 2 we present the results of numerical calculations of $B(Q^2)$ for two deuteron wave functions: Reid soft core (dash-dotted curve) (in parametrization of Ref. 10) and Paris wave function[9] (solid and dotted curves for the relativistic model, dashed curve for the nonrelativistic one). All the curves except the dotted one are calculated with the Gari-Krumpelmann nucleon form factors,[11] while the dotted curve is calculated with the dipole ones.

We want to emphasize the following.

(i) The nuclear-core hypothesis predicts the minimum of $B(Q^2)$.

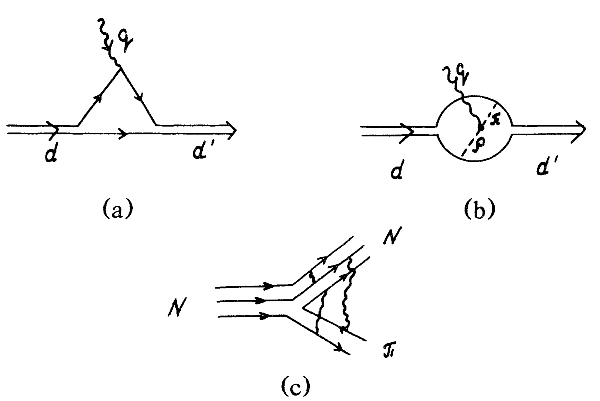

FIG. 1. Diagrams describing (a) the relativistic impulse approximation and (b) the meson-exchange current in the γdd vertex, and (c) the asymptotical behavior of the πNN form factor for the deeply virtual pion.

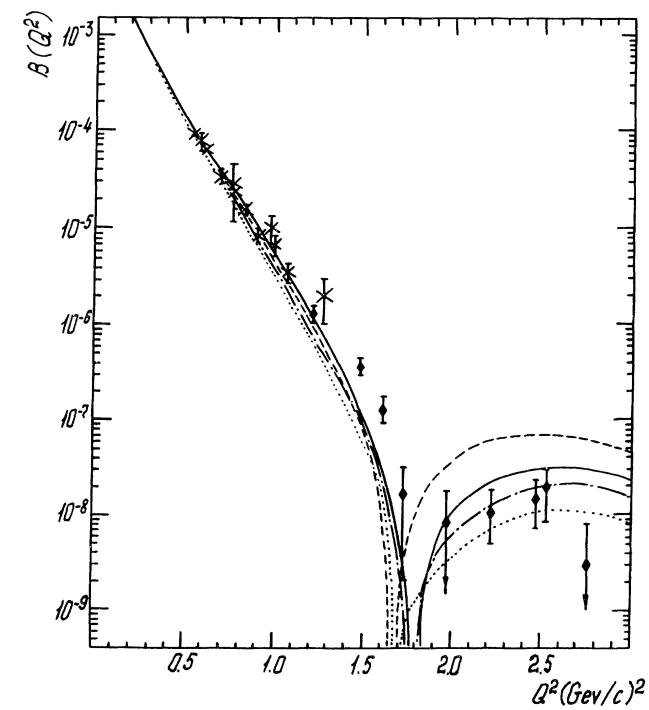

FIG. 2. The function $B(q^2)$ for different models of the deuteron wave function and nucleon form factors. Solid and dashed curves correspond to relativistic and nonrelativistic calculations with Paris WF (Ref. 9); dash-dotted curve—the relativistic Reid soft-core model, parametrized according to Ref. 10; dotted curve—the relativistic Paris WF with the dipole nucleon form factors. All other curves, except the dotted one, were calculated with the nucleon form factors parametrized as in Ref. 11.

(ii) The relativistic effect specific for light-cone dynamics is the shift of the minimum of $B(Q^2)$ to a larger value of Q^2 as compared to the nonrelativistic approach. This shift agrees reasonably well with the current experimental data. The relativistic approach predicts also the rise of $B(Q^2)$ for $Q^2 \gtrsim 2$ $(\mathrm{GeV}/c)^2$, which is smaller than in nonrelativistic calculations, though its height depends on the choice of the realistic deuteron WF and to some extent on the uncertainties in nucleon form factors (see Fig. 2). Similar results were found in Ref. 5.

(iii) In the relativistic approach of Ref. 12, the minimum of $B(Q^2)$ is shifted to smaller Q^2 as compared to the nonrelativistic approach, but this result is sensitive to the WF models used and to approximations made (cf. Refs. 12–14). In this respect the light-cone approach seems to be more restrictive.

Let us consider other approaches.

Perturbative QCD in the democratic chain approximation (quark-counting rules) reasonably describes the Q^2 dependence of $A(Q^2)$ at $Q^2 \gtrsim 0.8$ $(\mathrm{GeV}/c)^2$.[15] This approach predicts smooth behavior of $B(Q^2)$ on Q^2. Therefore it cannot explain the zero in the magnetic form factor. Note that analysis of quark-gluon propagators for the democratic chain diagrams indicates that this model may be applicable at $Q^2 > 4$ GeV^2 only [see Ref. 3(b), p. 274]. Remember also that perturbative QCD underestimates the absolute value of the nucleon form factor at $Q^2 < 10$ $(\mathrm{GeV}/c)^2$ by a factor $\sim 10^{-2}$.[16]

Contribution of meson currents to the deuteron magnetic form factor seems to be noticeable at small Q^2.[17] However, it should rapidly decrease with Q^2 if the quark structure of mesons and nucleons is adequately taken into account. Really, at large Q^2 the contribution of the meson-exchange currents [Fig. 1(b)] is roughly proportional to the product of the form factors of πNN, ρNN, and $\rho\pi\gamma$ vertices, $F_{\pi NN}(Q^2/4)F_{\rho NN}(Q^2/4)F_{\rho\pi\gamma}(Q^2)$, and this strongly depends on the slopes of these form factors. [Since our expectations for $F_{\rho\pi\gamma}(Q^2)$ are similar to those of the one-boson-exchange potential, we do not discuss them here.] To estimate the high-Q^2 behavior of $F_{\pi NN}(Q^2)$ [similar reasoning is valid for $F_{\rho NN}(Q^2)$] it is convenient to rewrite Feynman diagrams for $F_{\pi NN}(Q^2)$ in terms of old-fashioned perturbative theory on the light cone. In this case $\bar{u}\gamma_5 F_{\pi NN}(Q^2)u$ is the WF of the transition $N \to N\pi$, where $M_{\pi N}^2 \neq M_N^2$. This WF by construction depends on Q^2 only. Let us first estimate the high-Q^2 behavior of $F_{\pi NN}(Q^2)$ in terms of perturbative QCD. Leading (containing a minimal number of hard propagators) diagrams are shown in Fig. 1(c). The calculation of these diagrams leads to

$$\bar{u}\gamma_5 F_{\pi NN}(Q^2)u\,|_{Q^2\to\infty} \approx \left(\frac{1}{Q^2}\right)^3 \approx G_N(Q^2)G_\pi(Q^2)\,. \qquad (4)$$

Here $G_N(Q^2)$ $[G_\pi(Q^2)]$ are electromagnetic form factors of a nucleon [pion]. Such behavior should be valid at extremely large Q^2 only. At the same time, at smaller Q^2, all suppression factors due to the quark structure of the pion and nucleon should be present. Therefore it seems that Eq. (4) could be a reasonable interpolation formula at moderate Q^2.

It is possible to obtain a restriction on the slope of $F_{\pi NN}(Q^2)$ at $Q^2 \lesssim 0.3$ GeV^2, which at such Q^2 may be parametrized as $F_{\pi NN}(Q^2) \approx \exp(-\lambda Q^2)$. On the basis of the analysis of the sea content of nucleons,[18] $\lambda \gtrsim 2^{+0.6}_{-0.3}$ GeV^{-2}. If one takes into account both $N \to N\pi$ and $N \to \Delta\pi$ transitions, a more strong bound follows[8(b)] [in Ref. 8(b) several other restrictions on λ are presented]: $\lambda \gtrsim 3$ GeV^{-2}. Really, $\lambda \approx 3$ GeV^{-2} results in the πNN form factor varying slower than the low-Q^2 behavior of Eq. (4) and closer to the calculation of $F_{\pi NN}(Q^2)$ in the Skyrme model.[19] (The above reasoning predicts the same asymptotic behavior for πNN and ρNN form factors. In terms of quark models of a hadron, it is natural to expect that πNN and ρNN form factors similarly decrease with Q^2 at moderate Q^2 also.)

In Ref. 20 the contribution of meson currents to $B(Q^2)$ was calculated with $\pi NN,\rho NN$ form factors of the form

$$F_\alpha(Q^2) = (1+Q^2/\Lambda_{1,\alpha}^2)^{-1}(1+Q^4/\Lambda_{2,\alpha}^4)^{-2}$$

(where $\Lambda_{1,\pi NN} = 0.99$ GeV/c, $\Lambda_{1,\rho NN} = 0.77$ GeV/c, and

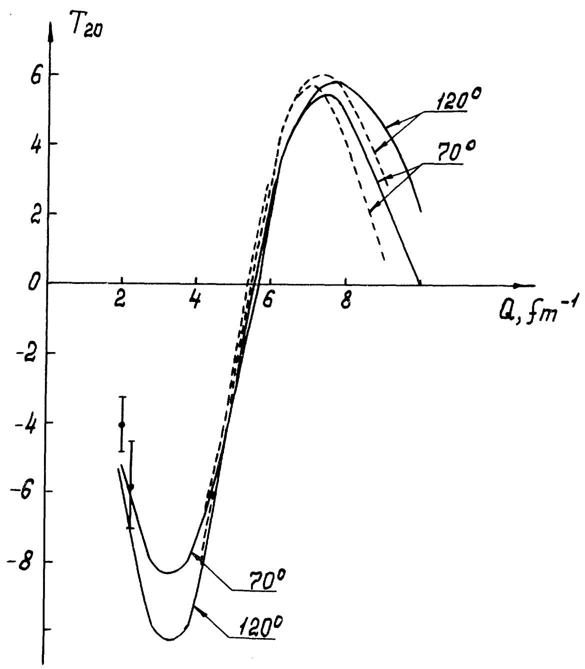

FIG. 3. The tensor polarization t_{20} of the deuteron calculated in the relativistic (solid curves) and nonrelativistic (dashed curves) approximations for the Paris model. The experimental data are taken from Ref. 24.

$\Lambda_{2,\pi NN} = \Lambda_{2,\rho NN} = 2.58$ GeV/c) suggested in Ref. 21. These calculations found that the contribution of the meson-exchange current (MEC) is comparable with the contribution of the two-nucleon component. At the same time if we account for more realistic $\pi NN, \rho NN$ form factors, we would suppress the contribution of MEC to $B(Q^2)$ at $Q^2 \approx 2$ GeV by the factor $\approx \frac{1}{7}$.

Within the framework of LCQM, MEC is a matrix element of the j_+ component of electromagnetic current for the magnetic transition $\rho\pi\gamma$:

$$\langle \psi_d(\rho NN) \,|\, j_+^{\rho\pi\gamma}(\mathbf{Q}_\perp) \,|\, \psi_d(\pi NN) \rangle \,.$$

This matrix element is equal to zero if we neglect the ρ meson admixture to the deuteron WF. We want to draw attention to the fact that conventional perturbative theory in the deuteron rest frame contains Z diagrams (especially important for the pseudoscalar πNN interaction) and production of pairs by virtual photons. On the contrary, both these contributions are automatically equal to zero in the LCQM for the good component of current.

Recently the new $B(Q^2)$ data[1] were discussed in the model[22] with $\Delta\Delta$ admixture in the deuteron WF, $P_{\Delta\Delta} \approx 2\%$. Including also the MEC, the authors were able to fit the data. We want to note that this $\Delta\Delta$ admixture is considerably larger than the upper bound of $P_{\Delta\Delta} < 0.4\%$ (90% C.L.) obtained recently in a νD experiment.[23]

We also performed the calculation of the deuteron tensor polarization t_{20} for two scattering angles 70° and 120° (see Fig. 3). Relativistic effects for Q's where experimental data are available[24] prove to be small (see Fig. 3).

The authors are indebted to S. Rock for the information concerning experimental data, and to Yu. A. Simonov for useful discussions.

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