Magnetic Form Factor of the Deuteron

S. Auffret, J. M. Cavedon, J. C. Clemens, B. Frois, D. Goutte, M. Huet, Ph. Leconte, J. Martino, Y. Mizuno, X.-H. Phan, and S. Platchkov
Service de Physique Nucléaire–Haute Energie, Commissariat à l'Energie Atomique, Centre d'Etudes Nucléaires de Saclay, F-91191 Gif-sur-Yvette Cedex, France

and

I. Sick
Department of Physics, University of Basel, Basel, Switzerland
(Received 7 November 1984)

We have measured the deuteron magnetic form factor $B(q^2)$ for values of the momentum transfer squared between 7 and 28 fm^{-2}. The data are compared with relativistic and nonrelativistic predictions including meson-exchange–current contributions. Significant disagreement is found for large momentum transfers.

PACS numbers: 21.10.Ky, 21.40.+d, 25.30.Bf

In spite of many experimental and theoretical studies[1] of the structure of the deuteron, its charge and magnetic form factors are still not well known. The $A(q^2)$ structure function is an incoherent combination of monopole and quadrupole form factors G_0 and G_2 whose diffraction structure cannot be isolated unless polarization measurements[2] are performed. For the magnetic form factor G_1 the experimental information is particularly scarce since data[3] are limited to momentum transfers smaller than 14 fm^{-2}. The first diffraction minimum of G_1 is predicted to occur somewhere between 30 and 50 fm^{-2}; near this value of momentum transfer, the falloff of G_1 becomes very sensitive to the model used for the N-N interaction. The differences in the form factors predicted depend strongly on the deuteron D-state wave function. Models with low D-state probability usually show a much more pronounced falloff than those having a D-state percentage close to 7%. Mesonic and relativistic effects also play a major role. Therefore data beyond 14 fm^{-2} should be very helpful in delineating these effects. Such data are reported in the present Letter.

The measurements were performed at the Saclay linear electron accelerator. The liquid-deuterium target used was operated at a temperature of 22 K and maintained at a pressure of 2.4 atm. The target volume had a cylindrical shape with a length of 70 mm along the beam axis and a diameter of 30 mm. The geometry was such that the electrons scattered from the windows were not seen by the spectrometer.

A fan circulated the liquid deuterium through a heat exchanger cooled by liquid hydrogen. With such an arrangement beam intensities up to 15 μA could be used without measurable changes in the target density. For a scattering angle of 155° the target thickness seen by the spectrometer was about 540 mg/cm^2. This thickness was surveyed by continously monitoring the target temperature and pressure.

The scattered electrons were analyzed with the 900-MeV/c magnetic spectrometer and identified by a coincidence between two planes of plastic scintillators and a Čerenkov counter. The trajectories of the electrons near the focal plane were measured in a pair of drift chambers, each consisting of two planes of detecting wires. This measurement made possible a reconstruction of the coordinates and the angles of the scattered electrons in the focal plane and at the target. This reconstruction was required to correct for the variation in electron energy over the spectrometer acceptance arising from differences in recoil energy and ionization energy losses. These losses limited the energy resolution to values between 2 and 6 MeV, depending on the kinematical conditions. Trajectory reconstruction improved the final resolution to 1 MeV and made possible the separation of the elastic peak and electrodisintegration at threshold.

Data were taken at thirteen different energies between 300 and 700 MeV at a scattering angle of 155°. Because of the high target density and large recoil energy, special care was taken in unfolding the radiative effects. We followed the prescriptions of Mo and Tsai[4] and Miller[5] for the kinematical and dynamical recoil effect, and that of Bergstrom[6] for the folding of the various radiative effects before and after nuclear scattering. The absolute efficiency of the detection system was determined from cross sections measured at forward angles and low momentum transfers and a comparison to a fit of the previous measurements of $A(q^2)$. The previous data on $A(q^2)$ have also been used to obtain the contribution of $A(q^2)$ at 155°. It was found to vary between 20% and 45% of the total cross section measured. The uncertainties of this subtraction and those due to the overall normalization were taken into account in the experimental errors quoted.

The resulting form factors $B(q^2)$ are listed in Table

TABLE I. Experimental results for electron-deuteron scattering at 155°. Incident energy, four-momentum transfer squared, total cross section, and deduced $B(q^2)$ form factor are tabulated. The total errors quoted include uncertainties from normalization and charge scattering subtraction.

Incident energy (MeV)	q^2 (fm^{-2})	Total cross section (mb/sr)	$B(q^2)$	Errors Stat. (%)	Errors Total (%)
300.0	6.72	5.61×10^{-8}	8.51×10^{-4}	3.5	9.3
330.0	7.94	2.88×10^{-8}	5.66×10^{-4}	3.0	8.5
360.0	9.25	1.65×10^{-8}	4.17×10^{-4}	3.1	8.1
395.0	10.86	8.02×10^{-9}	2.52×10^{-4}	4.5	9.0
430.0	12.55	4.38×10^{-9}	1.72×10^{-4}	5.4	9.5
470.0	14.59	1.98×10^{-9}	9.38×10^{-5}	5.4	9.7
500.0	16.18	1.18×10^{-9}	6.46×10^{-5}	4.6	9.0
535.0	18.10	5.49×10^{-10}	3.34×10^{-5}	6.1	10.9
570.0	20.09	3.29×10^{-10}	2.35×10^{-5}	5.9	10.6
600.0	21.84	1.94×10^{-10}	1.51×10^{-5}	7.8	13.1
635.0	23.94	9.81×10^{-11}	7.94×10^{-6}	9.2	16.2
670.0	26.09	6.76×10^{-11}	6.33×10^{-6}	14.2	22.6
700.0	27.97	3.77×10^{-11}	3.33×10^{-6}	12.7	24.3

I. They extend the experimentally known q region to 28 fm^{-2} (Fig. 1). The overall precision between 7 and 14 fm^{-2}, where previous data were available, is significantly improved. No onset of a diffraction feature as predicted by impulse-approximation calculations is observed.

In Fig. 1 the data are compared to the impulse-approximation predictions of six *N-N* models: Reid soft-core [(RSC), 6.5% *D*-stage probability],[7] Paris (5.8%),[8] Holinde-Machleidt [(MH2), 4.3%],[9] and three Lomon-Feshbach[10] models (FL1, FL5, and FL15) which have respectively 4.6%, 5.2%, and 7.5% *D*-state probability. All predictions are lower than the data, the difference becoming much more pronounced for models with low *D*-state probability. The HM2 model, which has the lowest *D*-state probability, is almost a factor of 100 too low.

The above predictions have been calculated with use of the nucleon electromagnetic form factors of Iachello, Jackson, and Landé.[11] In the momentum-transfer range of our data we have compared the impulse-approximation predictions obtained using four other parametrizations.[12-15] We have found that the resulting $B(q^2)$ differ by less than 15% for those parametrizations which give a good fit to the data on proton and neutron form factors. Although not negligible, this difference is small compared to other theoretical uncertainties.

Meson-exchange currents (MEC's), which are not taken into account for the predictions shown in Fig. 1, have been calculated by Gari and Hyuga[16] (GH). These authors use an RSC wave function and consider π, ρ, ω, and $\rho\gamma\pi$ isoscalar exchange currents, with appropriate hadronic vertex form factors. Particular attention has been paid to the $\rho\gamma\pi$ term, whose coupling constant has been recently recalculated[16] with use of the latest value of the $\rho\rightarrow\pi\gamma$ partial decay width.[17]

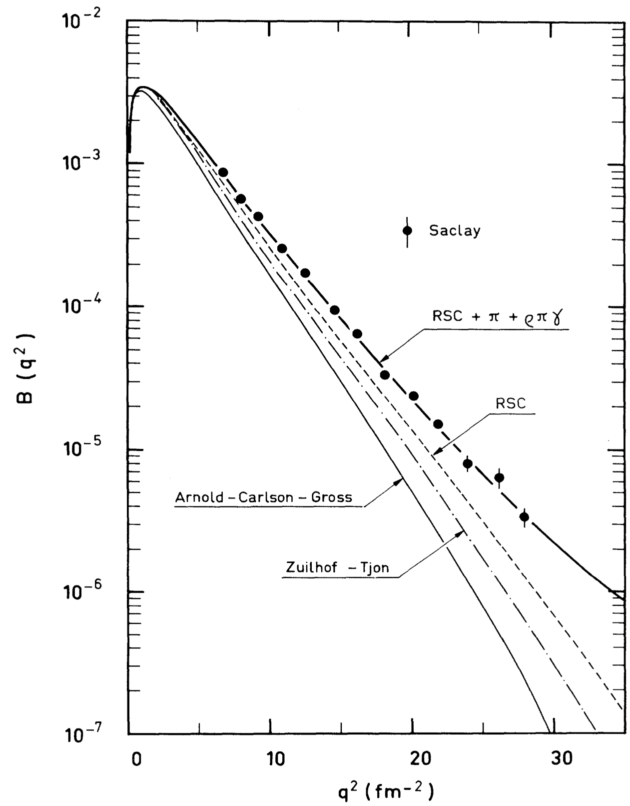

FIG. 1. Experimental data for $B(q^2)$. All curves have been calculated in the impulse approximation.

That term, which has no isovector part, dominates the π-pair term already at 5 fm^{-2} and gives the largest contribution to the cross section beyond 33 fm^{-2}. Terms involving ρ and ω exchange have significantly smaller contributions. The global effect of all MEC contributions is to increase the impulse-approximation prediction of $B(q^2)$ by a factor of 3 at 28 fm^{-2}, as shown in Fig. 2. When added to the RSC prediction, the MEC's bring the theory into a remarkable agreement with the data. Since the calculation of Gari and Hyuga ignores relativistic effects and does not include isobar (mainly $\Delta\Delta$) degrees of freedom in the deuteron wave function, the good agreement with the experimental data might be fortuitous.

The isobar components in the deuteron wave function have been calculated by Gari, Hyuga, and Sommer,[18] who found that the $\Delta\Delta$ contribution to the G_1 form factor is almost negligible (4% of the RSC result at 20 fm^{-2}). A calculation by Arenhövel and Miller[21] finds a much larger effect, an increase of the G_1 form factor by as much as 50% at 20 fm^{-2}. The large difference between the two calculations might be related to the different computational methods used and assumptions about the Δ magnetic moment. While Gari, Hyuga, and Sommer use the nucleon magnetic moment, Arenhövel and Miller use a larger value predicted by the quark model.[22] As the isobar contribution is mainly magnetic, further investigations are clearly needed for a better understanding of the $B(q^2)$ structure function.

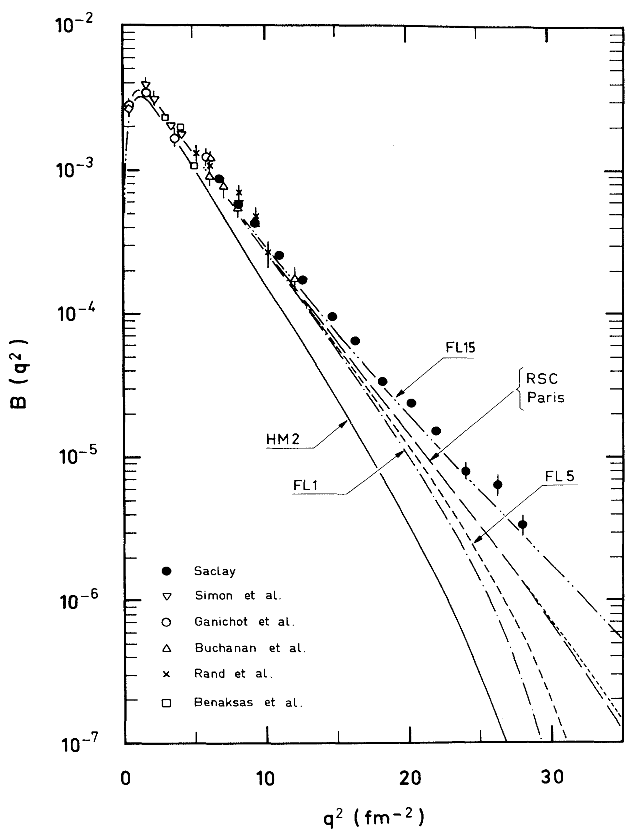

FIG. 2. Theoretical calculations of Refs. 18–20. For clarity only our measurements have been displayed.

The calculation of Gari and Hyuga does not take into account the relativistic effects. For an isoscalar process these are of the same order, $(q/M)^2$, as the meson-exchange currents. Relativistic calculations have recently been performed[19] by Arnold, Carlson, and Gross, who use four-component relativistic wave functions with a mixing of pseudoscalar and pseudovector pion-nucleon coupling. They compute the deuteron form factors retaining all orders of q/M. Furthermore, they allow the interacting nucleon to be off the mass shell. The result of their calculations for Iachello-Jackson-Lande form factors and mixing parameter $\lambda = 0.4$ is shown in Fig. 2. It indicates a much faster falloff for $B(q^2)$ than that predicted by Gari and Hyuga.

Relativistic calculations have been also performed by Zuilhof and Tjon[20] (ZT), who solve the Bethe-Salpeter equation in a ladder approximation, allowing both nucleons to be off the mass shell. Their prediction, shown also in Fig. 2, is somewhat closer to the experimental points, but still gives values of $B(q^2)$ significantly below the data.

The above situation is quite worrying; without inclusion of the $\Delta\Delta$ contribution, the nonrelativistic calculation appears to be in good agreement with data, while the relativistic calculations, *a priori* more reliable, are off by factors of 12 and 5, respectively, at 29 fm^{-2}. The following main differences between these approaches could explain the major part of the discrepancy. First, the pair two-body current naturally arises in a relativistic calculation, while in the calculation of GH it is added perturbatively. This can be a source of ambiguity; some cancellation occurs[23] between MEC and two-body dynamical effects, which are considerably treated in a full relativistic calculation but neglected by GH. Moreover, as recently shown by Riska,[24] the pair current is largely canceled by a model-independent two-body term related to the spin-orbit part of the N-N potential. Second, the $\rho\gamma\pi$ exchange term, included in the calculation of GH, is neglected in both relativistc calculations. *Ad hoc* inclusion of that term in the ZT calculation would reduce the discrepancy with the data at 28 fm^{-2} by about 30% only. Finally, the calculations also differ by the wave functions used; whereas the RSC potential used by GH yields 6.5% D-state probability, the models of Arnold, Carlson, and Gross and of ZT both give 4.8%. As shown in Fig. 1, impulse-approximation results strongly depend on the D-state wave function.

In conclusion, we have measured the magnetic structure function of the deuteron between 7 and 28 fm^{-2}. The accuracy of the results provides rigorous tests of theoretical predictions. No satisfactory interpretation for our data is available at present. The understanding of the deuteron form factors will require a more complete treatment of relativistic effects and isobar components.

We are grateful to M. Gari and E. Lomon for stimulating discussions. This work was supported in part by the Swiss National Science Foundation.

[1]E. Lomon, Ann. Phys. (N.Y.) **125**, 309 (1980).

[2]M. G. Schulze *et al.*, Phys. Rev. Lett. **52**, 597 (1984).

[3]D. Benaksas *et al.*, Phys. Rev. **148**, 1327 (1966); B. Grossetête *et al.*, Phys. Rev. **141**, 1425 (1966); C. D. Buchanan and M. R. Yearian, Phys. Rev. Lett. **15**, 305 (1965); R. E. Rand *et al.*, Phys. Rev. Lett. **18**, 469 (1967); B. Ganichot *et al.*, Nucl. Phys. **A178**, 545 (1972); E. C. Jones *et al.*, Phys. Rev. C **21**, 1162 (1980); G. G. Simon *et al.*, Nucl. Phys. **A364**, 285 (1981).

[4]L. W. Mo and Y. S. Tsai, Rev. Mod. Phys. **41**, 205 (1969).

[5]G. Miller, Ph.D. thesis, Stanford University, 1970 (unpublished).

[6]J. Bergstrom, MIT summer study, MIT, 1967 (unpublished).

[7]R. V. Reid, Ann. Phys. (N.Y.) **50**, 411 (1968).

[8]M. Lacombe *et al.*, Phys. Rev. C **21**, 861 (1980); M. Lacombe *et al.*, Phys. Lett. **101B**, 139 (1981).

[9]K. Holinde and R. Machleidt, Nucl. Phys. **A256**, 479 (1976).

[10]E. Lomon and H. Feshbach, Ann. Phys. (N.Y.) **48**, 94 (1968).

[11]F. Iachello, A. D. Jackson, and A. Lande, Phys. Lett. **43B**, 191 (1973).

[12]M. Gari, Phys. Lett. **141B**, 295 (1984).

[13]G. Höhler *et al.*, Nucl. Phys. **B144**, 505 (1976).

[14]S. Galster *et al.*, Nucl. Phys. **32**, 221 (1971).

[15]S. Blatnik and N. Zovko, Acta Phys. Austriaca **39**, 62 (1974).

[16]M. Gari and H. Hyuga, Nucl. Phys. **A264**, 409 (1976); M. Gari, private communication.

[17]D. Berg *et al.*, Phys. Rev. Lett. **44**, 706 (1980).

[18]M. Gari, H. Hyuga, and B. Sommer, Phys. Rev. C **14**, 2196 (1976).

[19]R. G. Arnold, C. E. Carlson, and F. Gross, Phys. Rev. C **21**, 1426 (1980).

[20]M. J. Zuilhof and J. A. Tjon, Phys. Rev. C **22**, 2369 (1980).

[21]H. Arenhövel and H. G. Miller, Z. Phys. **266**, 13 (1974).

[22]H. Arenhövel, private communication.

[23]M. J. Zuilhof and J. A. Tjon, Phys. Rev. C **24**, 736 (1981).

[24]D. O. Riska, University of Helsinki Report No. HH-ACC-84-2, 1984 (to be published).