The poor fit by an s^{-n} dependence is due to systematic differences between experiments and the fact that the data do not seem to follow a simple power law.

[6]R. A. Carrigan, Jr., Phys. Rev. Lett. 24, 168 (1970).

[7]G. Barbiellini *et al.*, Phys. Lett. 39B, 663 (1972).

[8]R. K. Carnegie *et al.*, Phys. Lett. 59B, 313 (1975).

[9]G. L. Kane and A. Seidl, Rev. Mod. Phys. 48, 309 (1976).

[10]A. Böhm *et al.*, Phys. Lett. 49B, 491 (1974).

[11]P. Fishbane and C. Quigg, Nucl. Phys. B61, 469 (1973).

[12]T. T. Wu and C. N. Yang, Phys. Rev. 137, 708 (1964).

Measurement of the Magnetic Structure Function of the Deuteron at $q^2 = 1.0\ (\text{GeV}/c)^2$*

F. Martin

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

R. G. Arnold, B. T. Chertok, E. B. Dally,† A. Grigorian,‡ C. L. Jordan,§ W. P. Schütz,‖ and R. Zdarko‡

American University,¶ Washington, D. C. 20016

and

B. A. Mecking

Physikalisches Institut, Universität Bonn, Bonn, West Germany

(Received 3 September 1976)

At a square of the momentum transfer of 1.0 $(\text{GeV}/c)^2$ the elastic scattering of electrons on deuterons has been measured at electron scattering angles of 8°, 60°, and 82°. From these data we have extracted a value of $B(q^2) = (0.59 \pm 1.20) \times 10^{-5}$ for the deuteron. This measurement extends the range in momentum transfer by almost a factor of 2 over the previous measurements.

In a previous Letter[1] we have reported on measurements of $A(q^2)$ for the deuteron for q^2 out to 6.0 $(\text{GeV}/c)^2$. $A(q^2)$ is the structure function defined by the one-photon-exchange approximation, $d\sigma/d\Omega = \sigma_{\text{mott}}(A + B\tan^2\frac{1}{2}\theta)$. In this Letter we report on the measurement of $A + B\tan^2\frac{1}{2}\theta$ at scattering angles of 8°, 60°, and 82° for a square of the momentum transfer, q^2, of 1.0 $(\text{GeV}/c)^2$, and extract the deuteron's magnetic structure function B.

The coupling of spin and orbital angular momentum in the deuteron ground state leads to a requirement of 4% D state in $|\psi_d|^2$ in order to explain the deuteron's magnetic dipole moment, from the relation

$$\mu_d = \mu_p + \mu_n - \tfrac{3}{2}P_D(\mu_p + \mu_n - \tfrac{1}{2}). \tag{1}$$

However, N-N phenomenology is generally consistent with $P_D = 6.5 \pm 1.0\%$, which results in a 1.6% deficiency in μ_d compared to experiment. This shortcoming is usually ascribed to very short-range n-p phenomena such as meson-exchange currents, first calculated by Adler and Drell,[2] baryon resonance states in ψ_d, and relativistic corrections. The exchange currents and baryon resonance states are selected to be consistent with the isoscalar ($T = 0$) nature of the deuteron.

Large-angle elastic e-d scattering permits the testing of the dynamics of the deuteron's magnetic dipole moment, and at large q^2 probes the short-distance structure of these nuclear electromagnetic currents. Previous measurements[3,4] of the deuteron's magnetic structure function $B(q^2)$ in the interval $0 \leq q^2 \leq 14\ \text{fm}^{-2}$ (0.55 GeV^2) appear to be fully consistent with calculations using the impulse approximation.[5] These calculations use standard deuteron wave functions from N-N phenomenology and the measured nucleon form factors to compute $B(q^2)$. This approach appears to describe adequately any interaction effects in the deuteron at larger q^2 but leaves unexplained the discrepancy noted above for the static magnetic dipole moment.

Our $A(q^2)$ is measured by scattering electrons at 8°, detecting the electron in the Stanford Linear Accelerator Center (SLAC) 20-GeV/c spectrometer, and detecting, in coincidence with the electron, the deuteron in the SLAC 8-GeV/c spectrometer. The large-angle data were taken at

TABLE I. Summary of the measurements of $A + B\tan^2\frac{1}{2}\theta$ at $q^2 = 1.0$ (GeV/c)^2.

Scattering angle	Proton data World's	Proton data Ours	Deuteron data World's	Deuteron data Ours
8°	0.076 ± 5%	0.071 ± 5.8%	0.657×10^{-4} ± 13%	0.797×10^{-4} ± 7.0%
60°	0.121 ± 5%	0.119 ± 7.0%	···	0.714×10^{-4} ± 8.3%
82°	0.180 ± 5%	0.173 ± 6.4%	···	0.856×10^{-4} ± 8.6%

60° and 82°, where the electron was detected in the SLAC 1.6-GeV/c spectrometer and the deuteron was detected as before. In order to establish confidence in our model for computing the double-arm acceptances of these spectrometers, we also measured electron-proton scattering under the same conditions as those for the deuteron.

A Monte Carlo model of the experiment was constructed to compute the solid angle of the detectors integrated over their momentum acceptance and averaged over the target length. Also included in this model were radiative corrections[6]; nuclear absorption, nuclear scattering, multiple Coulomb scattering, and energy loss from ionization in all the materials that a particle passed through; the cross-section variation over the acceptance of the spectrometers; and the beam momentum profile. Minor adjustments were made in the model to the incident beam energy, within the uncertainty determined by the momentum-defining slits, to match the shapes of the momentum and angular distributions of the scattered electrons and recoil protons with those from our proton data. With the model thus calibrated by the shapes of the proton data, we determined the total solid angle and computed the cross sections for e-p elastic scattering. Our values for $A + B\tan^2\frac{1}{2}\theta$ are compared with the world's data[7] in Table I and Fig. 1. The overall good agreement of our proton measurements with previous work establishes confidence in our model for the solid angle and the corrections. We then use the same model, suitably modified for deuteron kinematics, to calculate the deuteron cross sections. The results are displayed in Table I and Fig. 1.

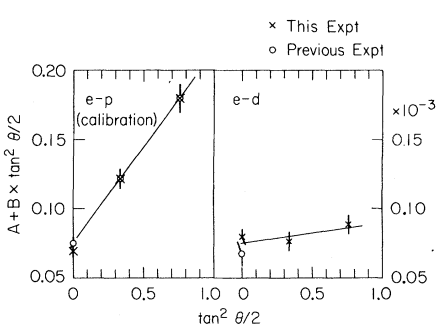

FIG. 1. Plots of e-p and e-d elastic scattering at large angles.

The graph in Fig. 1 showing the e-d data indicates a much shallower slope than that of the proton data. Also plotted on this graph is a previous measurement of $A(q^2)$ for the deuteron.[8] Using our data, we compute for the deuteron that

$$A = (0.776 \pm 0.046)\times10^{-4},$$

$$B = (0.59 \pm 1.20)\times10^{-5}.$$

Using our data plus the one point from Ref. 8 we obtain

$$A = (0.751 \pm 0.040)\times10^{-4},$$

$$B = (1.00 \pm 1.12)\times10^{-5}.$$

The deuteron magnetic form factor, G_M, is related to B by the following:

$$B = \eta\tfrac{4}{3}(1+\eta)G_M^2; \quad \eta = q^2/4M_d^2. \tag{2}$$

Using the value of B from the combined data we find that

$$G_M^2 = (0.99 \pm 1.10)\times10^{-4}.$$

Previous measurements of B made by Rand[3] and Buchanan[4] reached a maximum q^2 of 0.54 (GeV/c)^2. Consequently, we have extended the range of the square of momentum transfer by almost a factor of 2. The previous data plus our datum both with and without the previous value for A are shown in Fig. 2. Also shown in Fig. 2 are various calculations of the deuteron structure function B available prior to our experiment.

In general, the attempts to calculate the magnetic form factor using the impulse approximation and phenomenological forms for the nucleon form factor[3,4] resulted in a $B(q^2)$ that decreased with q^2 somewhat faster than the previous data. Rand, Yearian, Bethe, and Buchanan,[5] using the Hamada-Johnston wave function, recomputed the impulse approximation using empirical dipole fits

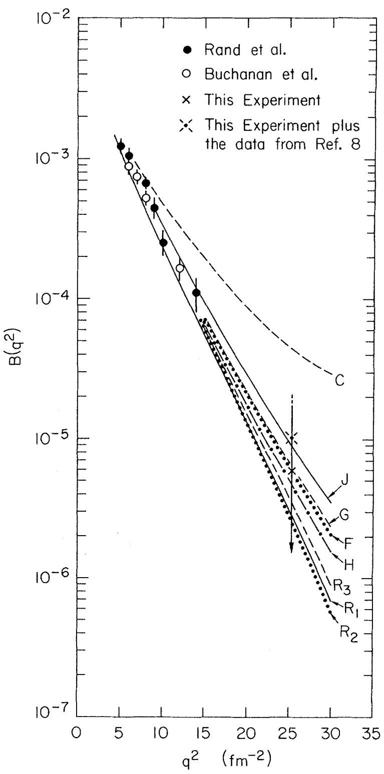

FIG. 2. Plot of $B(q)$ vs q, showing previous data and various predictions explained in the text.

to the neutron form factor instead of model-independent numerical forms. They found the impulse approximation to be in agreement with the previous data. The differences between these attempts to compute $B(q^2)$ would, at first glance, seem to be minimal. However, the phenomenological models and the dipole model for the neutron form factors do not represent the neutron data well and the neutron form factors can exert considerable influence on the deuteron form factors in the impulse approximation.

The discrepancies in the results of the impulse approximation and the data motivated a number of authors to incorporate meson-exchange currents in the models for the deuteron.[2,9-11] Blankenbecler and Gunion[9] (BG) made an exchange-current calculation using ideas of vector dominance and high-energy scattering of ρ and ω mesons. Chemtob, Moniz, and Rho[10] (CMR) made a more traditional nuclear physics calculation in which they included the $\rho\pi\gamma$ and the $\sigma\omega\gamma$ exchange diagrams. However, their $\rho\pi\gamma$ coupling constant was taken to be consistent with $\Gamma < 250$ MeV, now known to be too large. Jackson, Lande, and Riska[11] (JLR) calculated the effect of the pair diagrams with pion exchange and the so-called "recoil" current. All of these calculations treated the meson vertices as point interactions without a q^2-dependent form factor; and, relative to the impulse approximations, all of them gave enhancements to the deuteron $A(q^2)$ and $B(q^2)$ structure functions with increasing q^2.

Following the publication[1] of the results for the deuteron $A(q^2)$, which indicated that the enhancement of A by exchange effects as calculated by CMR and BG was too large, Gari and Hyuga[12] did another calculation of $A(q^2)$ and $B(q^2)$ which was an improvement over the previous work in three important respects: (1) They included the pair current with π, ρ, and ω exchange as well as the $\rho\pi\gamma$ current; they did not include the small $\sigma\omega\gamma$ current and excluded the recoil current described by JLR.[11] (2) They used a recently measured value of $\Gamma_{\rho\pi\gamma} = 35 \pm 10$ keV to determine the $\rho\pi\gamma$ coupling constant. (3) They used phenomenological form factors at the meson-nucleon vertices.

In order to obtain a juxtaposition of the various models and the data we have computed $B(q^2)$ in the impulse approximation using the Reid soft-core,[13] modified Hamada-Johnston,[14] and Feshbach-Loman[15] wave functions, and several sets of nucleon form factors. These curves, along with the calculations including meson-exchange currents from Refs. 10-12, are presented along with the data in Fig. 2. The curves are summarized below (all of these calculations were made without the benefit of relativistic corrections): R_1—Reid soft-core (RSC) wave functions (Ref. 13) and empirical dipole form factors with form-factor scaling. R_2—RSC with the five-parameter dipole semiphenomenological fit to nucleon form factors given by Iachello, Jackson, and Lande[16] (IJL). R_3—RSC with a combination of nucleon form factors determined by separate fits to neutron and proton data, Ref. 17. F—Feshbach-Loman boundary condition model No. 15 (Ref. 15), with 7.548% D state; same nucleon form factors as R_3. H—Modified Hamada-Johnston wave functions with 6.5% D state (Ref. 14); same nucleon form factors as in R_3. J—RSC plus exchange currents as computed in Ref. 11 (JLR) using the five-parameter IJL nucleon form factors. C—RSC plus exchange currents computed in Ref. 10 (CMR) using empirical dipole nucleon form factors. G—RSC plus exchange currents computed in Ref. 12 (Gari and Hyuga) using empirical dipole form factors.

Examination of Fig. 2 reveals the following:

(1) The influence of various nucleon form factors on the value of B, in particular various ver-

sions for the neutron G_{En} and G_{Mn}, increases with q^2. The curve R_3 using the "best-fit" form factors is about 40% higher than the curve R_2 using IJL form factors at $q^2 = 30$ fm^{-2}.

(2) The value of B is also sensitive to the choice of the deuteron wave functions. The curve H using Hamada-Johnston wave functions is about 70% higher at $q^2 = 30$ fm^{-2} than the curve R_3 using Reid soft-core wave functions and the same nucleon form factors, while the curve F using the Feshbach-Loman wave functions is a factor of 2.2 higher than R_3.

(3) The calculation of Gari and Hyuga is, to date, the most refined exchange calculation, and it lies well inside the error bars of all the data. The CMR calculation is beyond the upper edge of the error bar and is excluded with something over 66% confidence. This conclusion is consistent with the results of Ref. 1 for $A(q^2)$, which is evidence that if exchange currents are to be included in the calculation, then meson-nucleon vertex form factors must be used in this range of q^2 and, moreover, their contribution is small. The precision of the new datum does not allow one to distinguish between any of the impulse calculations or the meson-exchange calculations of Gari and Hyuga and JLR.

Finally we observe that the impulse-approximation curves, independent of which nucleon form factors are used, appear to be heading for a minimum in the q^2 range 40 to 50 fm^{-2}, while the exchange curves are all holding up in that region. Thus, a more definitive answer to the question of the exchange-currents contribution to the deuteron B form factor could be obtained by even a low-precision measurement in that region.

---

*Work supported by the U. S. Energy Research and Development Administration.

†On leave from Naval Postgraduate School, Monterey, Calif. 93940.

‡Present address: High Energy Physics Laboratory, Stanford University, Stanford, Calif. 94305.

§On leave from I. Physikalisches Institut, Technische Hochschule, Aachen, West Germany. (Present address: Lecroy Research Systems, Inc., 1 First Street, Los Altos, Calif. 94022.)

‖Present address: Kernforschungszentrum Karlsruhe, 75 Karlsruhe, West Germany.

¶Research supported by the National Science Foundation under Grant No. MPS 75-07325.

[1]R. G. Arnold *et al.*, Phys. Rev. Lett. 35, 776 (1975).

[2]R. J. Adler and S. D. Drell, Phys. Rev. Lett. 13, 349 (1964); R. J. Adler, Phys. Rev. 141, 1499 (1966).

[3]R. E. Rand *et al.*, Phys. Rev. Lett. 18, 467 (1967), and Phys. Rev. D 8, 3229 (1973).

[4]C. D. Buchanan *et al.*, Phys. Rev. Lett. 15, 303 (1965).

[5]R. E. Rand *et al.*, Phys. Rev. D 8, 3229 (1973).

[6]For electron radiative corrections, we used the formalism described in G. Miller's thesis, SLAC Report No. SLAC-129, 1971 (unpublished). The radiative loss associated with the nucleon (nucleus) in the double-arm coincidence was estimated using the formalism contained in Y. Tsai's paper, Phys. Rev. 122, 1898 (1961). In total, the radiative corrections amounted to approximately 35%.

[7]The e-p values we used for calibration were actually based on computations of G_{Ep} and G_{Mp} using the Iachello-Jackson-Lande (IJL) fits to the world's data [F. Iachello, A. D. Jackson, and A. Lande, Phys. Lett. 43B, 191 (1973)]. The IJL fit gives a value of 0.0779 for $A + B\tan^2\frac{1}{2}\theta$ at 15.44°, which compares with 0.0776 ± 2% as measured by P. N. Kirk *et al.*, Phys. Rev. D 8, 63 (1973).

[8]J. E. Elias *et al.*, Phys. Rev. 177, 2075 (1969).

[9]R. Blankenbecler and J. F. Gunion, Phys. Rev. D 4, 718 (1971).

[10]M. Chemtob, E. J. Moniz, and M. Rho, Phys. Rev. C 10, 344 (1974).

[11]A. D. Jackson, A. Lande, and D. O. Riska, Phys. Lett. 55B, 23 (1975).

[12]M. Gari and H. Hyuga, Phys. Rev. Lett. 36, 345 (1976), and Nucl. Phys. A264, 409 (1976).

[13]R. Reid, Ann. Phys. (N.Y.) 50, 411 (1968).

[14]T. Hamada and I. D. Johnston, Nucl. Phys. 34, 382 (1962); J. W. Humberston and J. B. G. Wallace, Nucl. Phys. A141, 362 (1970).

[15]The overlap integrals were kindly provided by E. Loman. This model is preferred for the extraction of the neutron form factor G_{En} from low-energy elastic e-d scattering. R. Berard *et al.*, Phys. Lett. 47B, 335 (1973).

[16]Iachello, Jackson, and Lande, Ref. 7.

[17]G_{Ep} and G_{Mp} are taken from IJL (Ref. 16); $G_{En} = -\mu_n G_{Ep}/(1+5.6\tau)$, where $\tau = q^2/4M_p^2$, from S. Galster *et al.*, Nucl. Phys. B32, 221 (1971); $G_{Mn} = \mu_n G_{Ep}$, from W. Bartel *et al.*, Nucl. Phys. B58, 429 (1973), and K. Hanson *et al.*, Phys. Rev. D 8, 753 (1973).