Measurements of the Deuteron Elastic Structure Function $A(Q^2)$ for $0.7 \leq Q^2 \leq 6.0\ (\mathrm{GeV}/c)^2$ at Jefferson Laboratory

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The deuteron elastic structure function $A(Q^2)$ has been extracted in the range $0.7 \leq Q^2 \leq 6.0$ $(\mathrm{GeV}/c)^2$ from cross section measurements of elastic electron-deuteron scattering in coincidence using the Hall A Facility of Jefferson Laboratory. The data are compared to theoretical models, based on the impulse approximation with the inclusion of meson-exchange currents, and to predictions of quark dimensional scaling and perturbative quantum chromodynamics. [S0031-9007(99)08477-X]

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Electron scattering from the deuteron has long been a crucial tool in understanding the internal structure and dynamics of the nuclear two-body system. In particular, the deuteron form factors, measured in elastic scattering, offer unique opportunities to test models of the short-range nucleon-nucleon interaction, meson-exchange currents and isobaric configurations, as well as the possible influence of explicit quark degrees of freedom [1,2].

The cross section for elastic electron-deuteron (e-d) scattering is described by the Rosenbluth formula,

$$\frac{d\sigma}{d\Omega} = \sigma_M\left[A(Q^2) + B(Q^2)\tan^2\left(\frac{\theta}{2}\right)\right], \qquad (1)$$

where $\sigma_M = \alpha^2 E' \cos^2(\theta/2)/[4E^3 \sin^4(\theta/2)]$ is the Mott cross section. Here E and E' are the incident and scattered electron energies, θ is the electron scattering angle, $Q^2 = 4EE' \sin^2(\theta/2)$ is the four-momentum transfer squared and α is the fine-structure constant. The elastic electric and magnetic structure functions $A(Q^2)$ and $B(Q^2)$ are given in terms of the charge, quadrupole, and magnetic form factors $F_C(Q^2)$, $F_Q(Q^2)$, $F_M(Q^2)$:

$$A(Q^2) = F_C^2(Q^2) + \frac{8}{9}\tau^2 F_Q^2(Q^2) + \frac{2}{3}\tau F_M^2(Q^2), \qquad (2)$$

$$B(Q^2) = \frac{4}{3}\tau(1+\tau)F_M^2(Q^2), \qquad (3)$$

where $\tau = Q^2/4M_d^2$, with M_d being the deuteron mass.

In the nonrelativistic impulse approximation (IA), the deuteron form factors are described in terms of the deuteron wave function and the electromagnetic form factors of the nucleons. Theoretical calculations based on the IA approach [1] using various nucleon-nucleon potentials and parametrizations of the nucleon form factors generally underestimate the existing $A(Q^2)$ data [3–6]. Recent relativistic impulse approximation (RIA) calculations improve or worsen the agreement with the data depending on their particular assumptions. There are two RIA approaches: manifestly covariant calculations [7–9] and light-front dynamics [10,11]. The form factors of the deuteron are very sensitive to the presence of meson-exchange currents (MEC) [1]. Some calculations also show sensitivity to the possible presence of six-quark [12] and isobar configurations in the deuteron [13]. The inclusion of MEC to the impulse approximation brings the theory into better agreement with the existing data.

At sufficiently large momentum transfers the form factors are expected to be calculable in terms of only quarks and gluons within the framework of quantum chromodynamics (QCD). The first attempt at a quark-gluon description of the deuteron form factors was based on quark dimensional scaling (QDS) [14]: The underlaying dynamical mechanism during e-d scattering is the rescattering of the constituent quarks via the exchange of hard gluons, which implies that $\sqrt{A(Q^2)} \sim (Q^2)^{-5}$. This prediction was later substantiated in the framework of perturbative QCD (pQCD), where it was shown [15] that, to leading order, $\sqrt{A(Q^2)} = [\alpha_s(Q^2)/Q^2]^5 \times \sum_{m,n} d_{mn}[\ln(Q^2/\Lambda^2)]^{-\gamma_n - \gamma_m}$, where $\alpha_s(Q^2)$ and Λ are the QCD strong coupling constant and scale parameter, and $\gamma_{m,n}$ and d_{mn} are QCD anomalous dimensions and constants. The existing SLAC $A(Q^2)$ data [4] exhibit some evidence of this asymptotic falloff for $Q^2 > 2$ $(\mathrm{GeV}/c)^2$.

The unique features of the Continuous Electron Beam Accelerator and Hall A Facilities of the Jefferson Laboratory (JLab) offered the opportunity to extend the kinematical range of $A(Q^2)$ and to resolve inconsistencies in previous data sets from different laboratories by measuring the elastic e-d cross section for $0.7 \leq Q^2 \leq 6.0$ $(\mathrm{GeV}/c)^2$. Electron beams of 100% duty factor were scattered off a liquid deuterium target in Hall A. Scattered electrons were detected in the electron High Resolution Spectrometer (HRSE). To suppress backgrounds and separate elastic from inelastic processes, recoil deuterons were detected in coincidence with the scattered electrons in the hadron HRS (HRSH). A schematic of the Hall A Facility as used in this experiment is shown in Fig. 1.

The incident beam energy was varied between 3.2 and 4.4 GeV. The beam intensity, 5 to 120 μA, was monitored using two resonant cavity beam current monitors (BCM). The two cavities were frequently calibrated against a parametric current transformer (Unser monitor) [16]. The beam was rastered on the target at high frequency and its position was monitored with two beam position monitors (BPM). The uncertainties in the incident beam current and energy were estimated to be $\pm 2\%$ and $\pm 0.2\%$, respectively. The target system contained liquid hydrogen and deuterium cells of length $T = 15$ cm and provided a record high luminosity of 4.0×10^{38} $\mathrm{cm^{-2}\,s^{-1}}$ $(4.7 \times 10^{38}$ $\mathrm{cm^{-2}\,s^{-1}})$ for hydrogen (deuterium). The raster system kept beam-induced

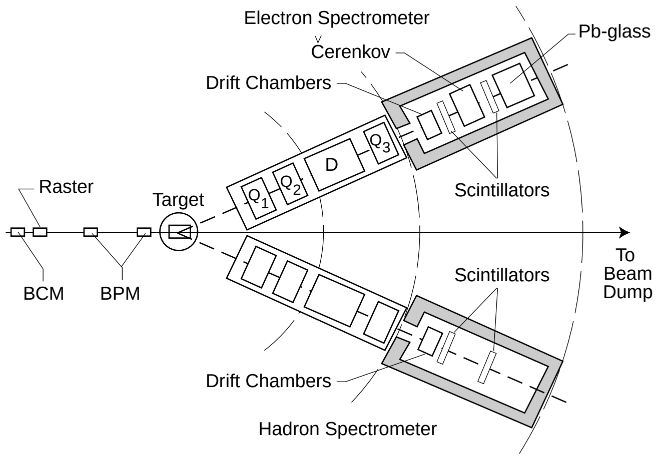

FIG. 1. Plan view of the Hall A Facility of JLab as used in this experiment. Shown are the beam monitoring devices, the cryotarget, the two magnetically identical spectrometers (consisting of quadrupoles Q_1, Q_2, Q_3, and dipole D), and the detector packages.

density changes at a tolerable level: up to 2.5% (5.0%) at 120 μA for deuterium (hydrogen).

Each HRS used two planes of plastic scintillators for triggering, and a pair of drift chambers for track reconstruction. In addition, HRSE was equipped with a gas threshold Čerenkov counter and a lead-glass calorimeter for electron identification. The efficiencies of the calorimeter and Čerenkov counter were ~99.5%, and of scintillators and tracking almost 100% for both spectrometers. Coincidence events were identified using the relative time of flight between the electron and recoil triggers. Elastic electron-proton (e-p) scattering in coincidence was measured for each e-d elastic kinematics. The e-p kinematics was chosen to match the electron-recoil solid angle Jacobian for the corresponding e-d kinematics. Data were taken with and without acceptance-defining collimaters in front of the spectrometers.

The elastic e-p and e-d cross sections were calculated using $d\sigma/d\Omega = [N_{ep(d)}C_{\mathrm{eff}}]/[N_i N_t(\Delta\Omega)_{\mathrm{MC}}F]$, where $N_{ep(d)}$ is the number of e-p (e-d) elastic events, N_i is the number of incident electrons, N_t is the number of target nuclei/cm^2, $(\Delta\Omega)_{\mathrm{MC}}$ is the effective double-arm acceptance from a Monte Carlo simulation, F is the portion of radiative corrections that depends only on Q^2 and T (1.088 and 1.092, on average, for e-p and e-d elastic, respectively), and $C_{\mathrm{eff}} = C_{\mathrm{det}}C_{\mathrm{cdt}}C_{\mathrm{rni}}$. Here C_{det} is the electron and recoil detector and trigger inefficiency correction (2.6%), C_{cdt} is the computer deadtime correction (typically 10% for e-d elastic), and C_{rni} is the correction for losses of recoil nuclei due to nuclear interactions in the target (0.7%–1.8% for protons and 2.8%–5.1% for deuterons).

The effective double-arm acceptance was evaluated with a Monte Carlo computer program that simulated elastic e-p and e-d scattering for the conditions of our measurements. The program tracked scattered electrons and recoil nuclei from the target to the detectors through the two HRS's using optical models based on magnetic measurements of the quadrupole and dipole elements, and on position surveys of collimation systems, magnets, and vacuum apertures. The effects from ionization energy losses and multiple scattering in the target and vacuum windows were taken into account for both electrons and recoil nuclei. Bremsstrahlung radiation losses for both incident and scattered electrons in the target and vacuum windows as well as internal radiative effects were also taken into account. Details on this simulation method can be found in Ref. [17]. Monte Carlo simulated spectra of scattered electrons and recoil nuclei were found to be in very good agreement with the measured spectra.

The e-p elastic cross sections measured with (without) the acceptance-defining collimators were found to agree within 0.3% (to be higher by 2.6%), on average, with values calculated using a recent fit [18] to world data of the proton form factors. All e-d cross-section data taken without collimators have been normalized by 2.6%.

Values for $A(Q^2)$ were extracted from the measured e-d cross sections under the assumption that $B(Q^2)$ does not contribute to the cross section [supported by the existing $B(Q^2)$ data [19]]. They are presented in Fig. 2, together with previous SLAC data [4] and theoretical calculations. The error bars represent statistical and systematic uncertainties added in quadrature. The statistical error ranged from $\pm 1\%$ to $\pm 28\%$. The systematic error has been estimated to be $\pm 5.9\%$ and is dominated by the uncertainty in $(\Delta\Omega)_{\mathrm{MC}}$ ($\pm 3.6\%$). Each of the two highest Q^2 points represents the average of two measurements with different beam energies (4.0 and 4.4 GeV). Tables of numbers are given in Ref. [20]. Our data agree very well with the SLAC data in the range of overlap and

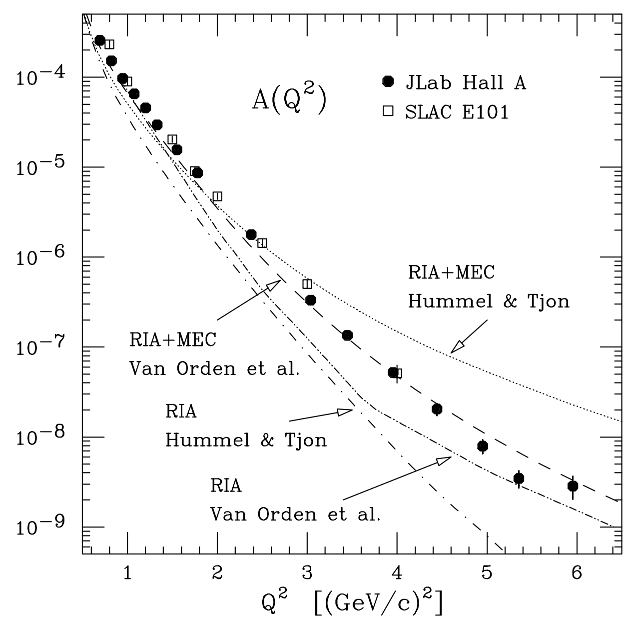

FIG. 2. The deuteron elastic structure function $A(Q^2)$ from this experiment compared to RIA theoretical calculations [7,8]. Also shown are previous SLAC data [4].

exhibit a smooth falloff with Q^2 with no apparent diffractive structure.

The double-dot-dashed and dot-dashed curves in Fig. 2 represent the RIA calculations of Van Orden, Devine, and Gross (VDG) [7] and Hummel and Tjon (HT) [8], respectively. The VDG curve is based on the Gross equation [21] and assumes that the electron interacts with an off-mass-shell nucleon or a nucleon that is one-mass-shell right before or after the interaction. The HT curve is based on a one-boson-exchange quasipotential approximation of the Bethe-Salpeter equation [22], where the two nucleons are treated symmetrically by putting them equally off their mass shell with zero relative energy. In both cases, the RIA appears to be lower than the data. Both groups have augmented their models by including the $\rho\pi\gamma$ MEC contribution. The magnitude of this contribution depends on the $\rho\pi\gamma$ coupling constant and vertex form factor choices [23]. The VDG model (dashed curve) uses a $\rho\pi\gamma$ form factor from a covariant separable quark model [24]. The HT model (dotted curve) uses a vector dominance model. The difference in the two models is indicative of the size of theoretical uncertainties. Although our data favor the VDG calculations, a complete test of the RIA+MEC framework will require improved and/or extended measurements of the nucleon form factors and of the deuteron $B(Q^2)$, planned at JLab.

Figure 3 shows our data in the "low" Q^2 range, where they overlap with data from other laboratories. The previous measurements tend to show two long-standing diverging trends, one supported by the SLAC data and the other one by the CEA [3] and Bonn [5] data. Our data agree with the Saclay data [6] and confirm the trend of the SLAC data. It should be noted that another JLab experiment has measured $A(Q^2)$ in the Q^2 range 0.7 to 1.8 $(\mathrm{GeV}/c)^2$ [25]. The two curves are from a recent nonrelativistic IA calculation [26] using the Argonne v_{18} potential without (dot-dashed curve, Fig. 3) and with (dashed curve, Fig. 3) MEC, and exhibit clearly the necessity of MEC inclusion also in the nonrelativistic IA.

Figure 4 (top) shows values for the "deuteron form factor" $F_d(Q^2) \equiv \sqrt{A(Q^2)}$ multiplied by $(Q^2)^5$. It is evident that our data exhibit a behavior consistent with the power law of QDS and pQCD. Figure 4 (bottom) shows values for the "reduced" deuteron form factor [27] $f_d(Q^2) \equiv F_d(Q^2)/F_N^2(Q^2/4)$, where the two powers of the nucleon form factor $F_N(Q^2) = (1 + Q^2/0.71)^{-2}$ remove in a minimal and approximate way the effects of nucleon compositeness [27]. Our $f_d(Q^2)$ data appear to follow, for $Q^2 > 2\ (\mathrm{GeV}/c)^2$, the asymptotic Q^2 prediction of pQCD [15]: $f_d(Q^2) \sim [\alpha_s(Q^2)/Q^2][\ln(Q^2/\Lambda^2)]^{-\Gamma}$. Here, $\Gamma = -(2C_F/5\beta)$, where $C_F = (n_c^2 - 1)/2n_c$, $\beta = 11 - (2/3)n_f$, with $n_c = 3$ and $n_f = 2$ being the numbers of QCD colors and effective flavors. Although several authors have questioned the validity of QDS and pQCD at the momentum transfers of this experiment [28,29], similar scaling behavior has been reported in deuteron photodisintegration at moderate photon energies [30].

In summary, we have measured the elastic structure function $A(Q^2)$ of the deuteron up to large momentum transfers. The results have clarified inconsistencies in previous data sets at low Q^2. The high luminosity and unique capabilities of the JLab facilities enabled measure-

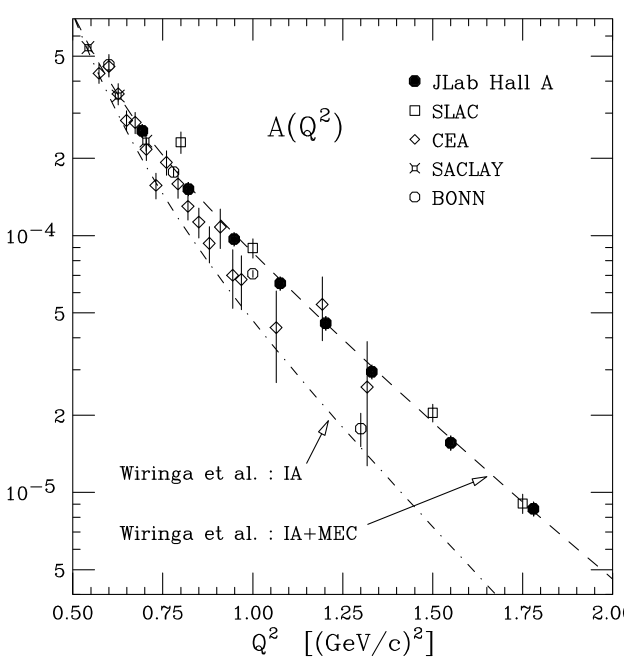

FIG. 3. The present $A(Q^2)$ data compared with overlapping data from CEA [3], SLAC [4], Bonn [5], Saclay [6], and IA+MEC theoretical calculations [26].

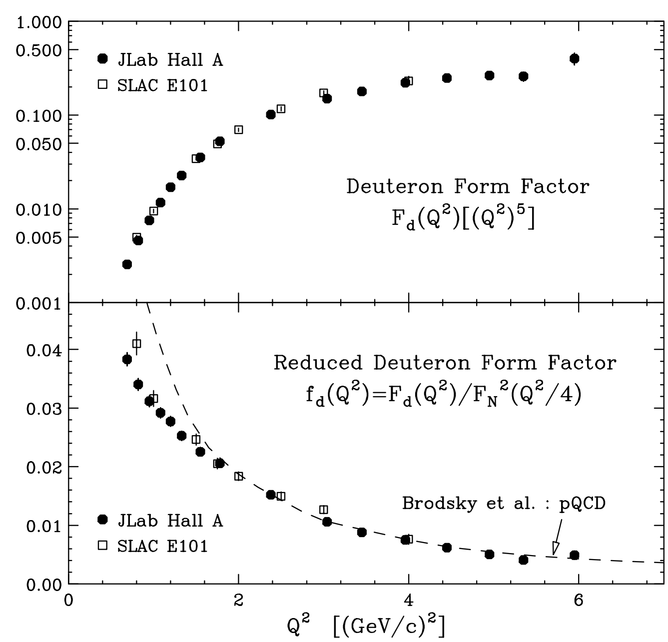

FIG. 4. The deuteron form factor $F_d(Q^2)$ times $(Q^2)^5$ (top) and the reduced deuteron form factor $f_d(Q^2)$ (bottom) from this experiment and from SLAC [4]. The curve is the asymptotic pQCD prediction of Ref. [15] for $\Lambda = 100$ MeV, arbitrarily normalized to the data at $Q^2 = 4\ (\mathrm{GeV}/c)^2$.

ments of record low cross sections [the average cross section for $Q^2 = 6\ (\mathrm{GeV}/c)^2$ is $\sim 2 \times 10^{-41}\ \mathrm{cm}^2/\mathrm{sr}$] which allowed extraction of values of $A(Q^2)$ lower by 1 order of magnitude than achieved at SLAC. The precision of our data will provide severe constraints on theoretical calculations of the electromagnetic structure of the two-body nuclear system. Calculations based on the relativistic impulse approximation augmented by meson-exchange currents are consistent with the present data. The results are also indicative of a scaling behavior, consistent with predictions of quark dimensional scaling and perturbative QCD. Future measurements, at higher Q^2, of $A(Q^2)$ and $B(Q^2)$ as well as of the form factors of the helium isotopes would be critical for testing the validity of the apparent scaling behavior.

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