Measurement of the Electron-Deuteron Elastic-Scattering Cross Section in the Range $0.8 \leqslant q^2 \leqslant 6$ GeV^2

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We report preliminary results of elastic *e-d* scattering at large momentum transfer performed at the Stanford Linear Accelerator Center with use of two high-resolution spectrometers in coincidence. Our results are in sharp disagreement with the meson-exchange calculations, they are in rough agreement with the nonrelativistic potential models, and they are in agreement with the predictions of the quark dimensional-scaling model which pictures the deuteron as a bound state of six quarks at large momentum transfer.

We present measurements of elastic electron-deuteron scattering at nine values of q^2, the square of the momentum transfer, in the range $0.8 \leqslant q^2 \leqslant 6.0$ GeV^2 extending measurements of the deuteron's structure function $A(q^2)$ by a factor of 4.5 in q^2 over previous investigations.[1] In the one-photon–exchange approximation and under the assumption of conservation of the nuclear electromagnetic current, the elastic-electron-scattering cross section is

$$\frac{d\sigma}{d\Omega}=\left(\frac{d\sigma}{d\Omega}\right)_{\rm Mott}[A(q^2)+B(q^2)\tan^2\tfrac{1}{2}\theta_e]. \qquad (1)$$

A and B are the deuteron's structure functions, and θ_e is the electron scattering angle. For this experiment, $\theta_e = 8°$ so that the second term in Eq. (1) is negligible. This investigation employed the technique of high-energy elastic electron scattering developed by Hofstadter and co-workers in the 1950's. The measurements were performed at the Stanford Linear Accelerator Center (SLAC) using the electron beam in the range 5 to 19 GeV with average currents from 0.2 to 30 μA and a momentum spread of ± 0.3%. Electron-deuteron elastic scattering and electron-proton elastic scattering were measured at each q^2 with use of two high-resolution spectrometers in coincidence, and $A(q^2)$ was deduced by a comparison of the elastic *e-d* and *e-p* coincidence yields and the world-average *e-p* cross sections.[2] A coincidence measurement was required because a single-arm electron measurement could not resolve elastic *e-d* events from the deuteron-breakup spectrum.

The 20-GeV spectrometer was operated as in previous SLAC experiments to detect electrons. The detection system consisted of two scintillation trigger counters, five planes of multiwire proportional chambers, and lead-glass and lead-Lucite total-absorption shower counters. The electron trigger was a threefold coincidence. An uncut spectrum of scattered electrons detected in the 20-GeV spectrometer at $q^2 = 3$ GeV^2 is displayed in the top curve of Fig. 1(b).

The trigger for a good particle in the 8-GeV spectrometer was a fourfold scintillator coincidence which was used to strobe four planes of scintillator hodoscopes. Deuterons and protons were identified from their time of flight inside the 8-GeV system. With use of the measured tracks of momentum-analyzed particles and the known transport properties of the two spectrometers, the double-arm missing-mass resolution was 10 MeV for 10-GeV incident electrons. The acceptance of the double-arm system was determined by the 8-GeV spectrometer with a value $\Delta\theta\,\Delta\varphi\,\Delta P/P = (0.015)(0.060)(0.40)$ sr.

The *e-d* elastic events were identified by recording the relative time of flight of particles causing triggers in the two spectrometers. A double-arm time-of-flight spectrum for an elec-

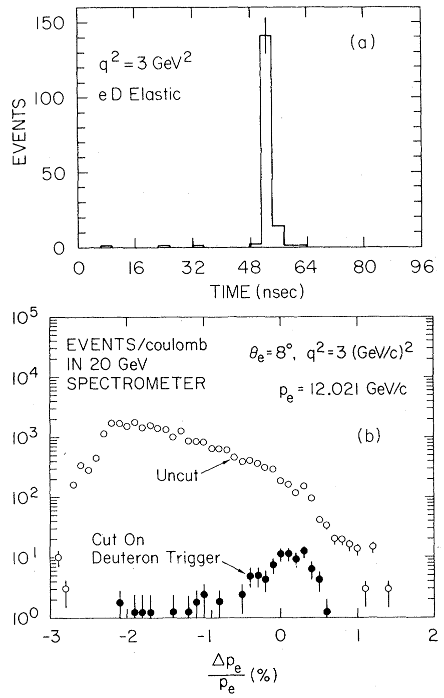

FIG. 1. (a) Electron-deuteron time-of-flight and (b) electron-momentum spectra.

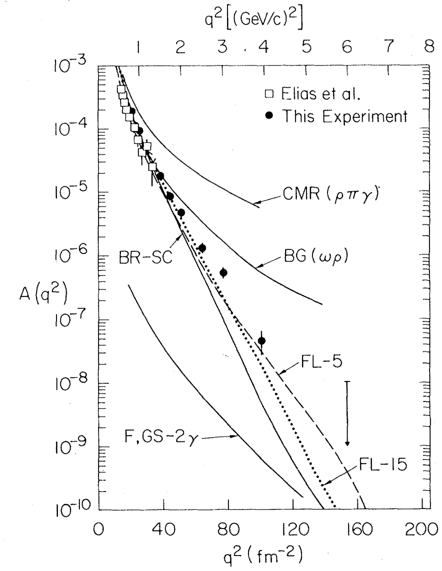

FIG. 2. Results of this experiment displayed with theoretical predictions.

tron-trigger start and a deuteron-trigger stop is displayed in Fig. 1(a) for the $q^2 = 3$-GeV^2 data. The peak represents the signal of double-arm elastic *e-d* events. The background of accidental coincidences is caused mainly by electrons in the 20-GeV spectrometer and protons in the 8-GeV spectrometer from uncorrelated quasielastic events in the target. This background was 20% of the *e-d* coincidence peak height at $q^2 = 1$ GeV^2 and decreased at larger q^2 until at $q^2 = 2.5$ GeV^2 and above it was negligible. A spectrum of elastically scattered electrons cut on the double-arm coincidence peak is displayed in the bottom curve in Fig. 1(b). The double-arm coincidence produced an enhancement in the signal-to-noise ratio of approximately 1000. Identical target cells were used containing circulating liquid hydrogen and deuterium.

The ratio measurements we report have the advantage that most of the important properties of the detection system that affect the coincidence counting rate do not change or change very little for the conditions of *e-p* and *e-d* scattering. Experimental corrections are applied for dead-time losses (5 to 10%), for wire-chamber track inefficiencies (~ 9%), and for losses due to deuteron breakup and proton interactions in the 8-GeV detector system (10 to 20%). The solid angle, radiative corrections (~ 35%), and losses due to multiple Coulomb scattering (3 to 8%) were modeled in a Monte Carlo simulation. In the ratio the radiative corrections nearly divide out. The ratio of *e-p* to *e-d* solid angle varied from 1.05 ($q^2 = 0.8$ GeV^2) to 1.35 ($q^2 = 6$ GeV^2). With use of the corrections described above, the absolute *e-p* cross sections have also been extracted for all q^2. They agree with the world-average cross sections[2] within the estimated 20% uncertainty of the absolute measurement.

Our results for $A(q^2)$ are presented in Figs. 2 and 3, along with current theoretical predictions. The error bars on the data points in Fig. 2 represent the statistical errors, the error on the world-average *e-p* cross sections, and the approximate 12% uncertainty in the ratio measurement added in quadrature. The error bar at $q^2 = 6$ GeV^2 represents a 2-standard-deviation limit, and corresponds to a cross section $d\sigma/d\Omega_d \leq 3 \times 10^{-40}$ cm^2/sr.

The qualitative expectations were that the impulse approximation representing the virtual photon striking one nucleon would be very small at $q^2 \gg 1$ GeV^2 and that accordingly $A(q^2)$ would be dominated by meson-exchange currents or other processes which shared the momentum transfer approximately equally with the two nucleons. Two different exchange-current predictions, labeled CMR[3] and BG[4] in Fig. 2, are contradicted by this

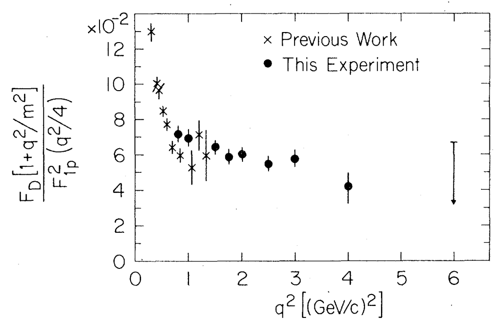

FIG. 3. Quark dimensional-scaling predictions using Eq. (4) compared to our data and selected data from Ref. 1.

experiment. Other exchange-current models which predict a flattening in A at lower q^2 would similarly be wrong.[5] The two-photon exchange[6] is seen to be well below the other predictions in Fig. 2.

For the spin-one deuteron in the impulse approximation, the deuteron structure function is

$$A(q^2) = G_0^{\,2} + \tfrac{8}{9}\eta^2 G_2^{\,2} + \tfrac{2}{3}\eta G_1^{\,2}, \tag{2}$$

where $\eta = q^2/4M_d^{\,2}$ and the G's are functions of q^2 and are the charge, quadrupole, and magnetic form factors, respectively.[1]

Some impulse-approximation predictions are indicated in Fig. 2 as Bethe-Reid soft core (BR-SC),[7] and Feshbach-Lomon potential models FL-5 and FL-15.[8] There is general agreement (within factors of 2 to 10) with the results of this experiment. Best-fit nucleon form factors have been used in Eq. (2).[2] Other N-N potentials may also fit A at large q^2 but we do not wish to distinguish between the various potential models because of the theoretical work still required on relativistic corrections or a relativistic theory of the nuclear force.[9] Relativistic corrections now available are believed to be unreliable above $q^2 \sim 1\ \text{GeV}^2$. Since G_{En} contributes about 60% to $A(q^2)$ in the impulse approximation, it may be possible, with use of the best available deuteron wave functions with relativistic corrections, to extend the information on the neutron form factors in the further analysis of our data.

Isobar admixtures and short-range forbidden states have been speculated to reside in the deuteron.[10] To the extent that both of these mechanisms give significant high-momentum components to the deuteron wave function that would flatten out $A(q^2)$, it can be observed in Fig. 2 that these theoretical speculations are made highly improbable by this experiment.

The rapid falloff of $A(q^2)$ is observed to approach a power-law behavior at large q^2,

$$F_d \sim (q^2)^{-5}, \tag{3}$$

as predicted by Brodsky and Farrar's[11] dimensional-scaling quark model, where $F_d = [A(q^2)]^{1/2}$. Verification of this model has been outstanding for both exclusive and inclusive reactions at large momentum transfer including the prediction that the electromagnetic form factors of the pion and proton vary as $(q^2)^{-1}$ and $(q^2)^{-2}$, respectively. We notice that the deuteron form factor approaches scaling in the same way as the pion and proton do at lower q^2. The theory is valid for $s \gg q^2 \gg m^2$, where s is the square of the center-of-mass energy. The present data and those of Elias *et al.*[1] are plotted in Fig. 3 with use of the phenomenological form suggested by Brodsky,[12]

$$F_d \sim F_{1p}^{\,2}(q^2/4)(1+q^2/m^2)^{-1}, \tag{4}$$

where $F_{1p} = (1+q^2/0.71)^{-2}$ and $m = m_p$. The onset of scaling is observed at $q^2 \sim 0.75\ \text{GeV}^2$ after a rapid drop by a factor of 20 in the interval 0 to 0.75 GeV^2. Other forms like Eq. (4) also display the quark degrees of freedom at modest values of q^2. The phenomenology is useful to see whether the data are consistent with $(q^2)^{-5}$ in a region where the six quark momenta are not far from their mass-shell values. Scaling of the data at large q^2 is consistent with the exponent in Eq. (3) equal to 5 ± 0.5.

In conclusion the data are described qualitatively by the nonrelativistic-wave-function approach over the whole range of 0 to 6 GeV^2 which is perhaps remarkable because of the relativistic nature of the interaction for $q^2 \gtrsim 1\ \text{GeV}^2$. Accordingly, it would appear that significant high-momentum components of the deuteron wave function from isobars, forbidden short-range states, or other exotic phenomena are severely limited. One can also interpret the results of this experiment as evidence of the deuteron as a six-quark bound state with the scale-invariant behavior appearing precociously at low q^2 leading us to the observation that phenomena from quark constituents may be visible elsewhere in nuclear physics.

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Evidence for the Isoscalar Giant Quadrupole Resonance in ^{16}O

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The spectra of 146-MeV α particles scattered inelastically from ^{16}O exhibit a giant-resonance-type structure between excitation energies of 15.9 and 27.3 MeV. The analysis of angular distributions shows its quadrupole nature and yields a strength exhausting about 65% of the isoscalar $E2$ energy-weighted sum rule.

Recently, several experimental[1-5] and theoretical[6-11] investigations have been published concerning giant quadrupole resonances (GQR) in ^{16}O. Some of these papers deal especially with the question of an isoscalar ($T = 0$) GQR excited in (α,γ_0) capture[2] and inelastic scattering,[4,5] however, without arriving at completely conclusive results.[12] The (α,γ_0) investigation suffered mainly from the fact that only one decay channel was studied. The ^{3}He inelastic scattering,[4] on the other hand, is not completely isospin selective. A recent study of inelastic α-particle scattering[5] at 97 MeV which was not subjected to these restrictions has only been able to exclude the existence of a resonance at $63A^{-1/3} = 25$ MeV predicted by the hydrodynamical model.[11] Recent theoretical investigations[7-10] expect the isoscalar GQR in the energy range between 20- and 25-MeV excitation energy. In this Letter we present results from an ^{16}O(α,α') experiment at 146