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Electron-Deuteron Scattering in the Inelastic Threshold Region at High Momentum Transfer*

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At squared momentum transfers $0.8 \leq q^2 \leq 6.0$ $(\text{GeV}/c)^2$, we measured nine spectra of inelastic electron-deuteron scattering cross sections in the threshold region between 0 and 2.3% in $\Delta p/p$ below the elastic peak and deduced the deuteron inelastic structure function νW_2. We found $\nu W_2(\omega')$ approaching a universal scaling curve and a close relation between νW_2 and the deuteron elastic structure function $A(q^2)$.

In this Letter, we report preliminary results of inelastic electron-deuteron scattering in the threshold region at high momentum transfer q. The data were taken from a Stanford Linear Accelerator Center experiment[1] whose main purpose was to measure the elastic scattering cross sections and the deuteron structure function $A(q^2)$ at nine values of q^2 in the region $0.8 \leq q^2 \leq 6.0$ $(\text{GeV}/c)^2$. The experimental conditions were such that we measured not only the elastic events, but also inelastic events from deuteron breakup and pion production between $0 \geq \Delta p/p_e \geq -2.3\%$, where p_e is the scattered-electron momentum at the center of the elastic peak. The nine inelastic electron spectra span an unusual dynamic region of large q^2 and small energy transfer $\nu = E_i - E_f$, the difference between initial and final electron energies. This region has not been explored before. Bjorken scaling is expected when both q^2 and ν are large compared with M_N^2, the square of the nucleon mass, as in deep-inelastic electron scattering. The data presented here are on a scale where q^2 is expected to resolve the nucleons into fermion quark currents, while ν is typical of excitation energies where nucleon-nucleon final-state-interaction effects may be significant. The deuteron, then, is an ideal system to study the approach to scaling and the interplay between nuclear and particle physics.

We used the 20-GeV/c spectrometer of the Stanford Linear Accelerator Center End Station A to detect scattered electrons at a fixed $\theta_e = 8°$ from liquid deuterium, from liquid hydrogen (for system calibration), and from a dummy target to determine the empty-target background. To filter the elastic events out of the inelastic and background events, we used the 8-GeV/c spectrometer in coincidence with the 20-GeV/c spectrometer to detect the recoil deuterons with elastic kinematics.

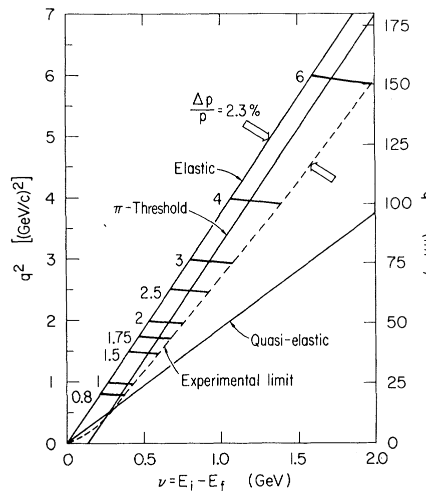

FIG. 1. Kinematics of this experiment. The data were taken in the regions indicated by the horizontal bars. The tail of the quasielastic peak contributes to the cross section in the measured region.

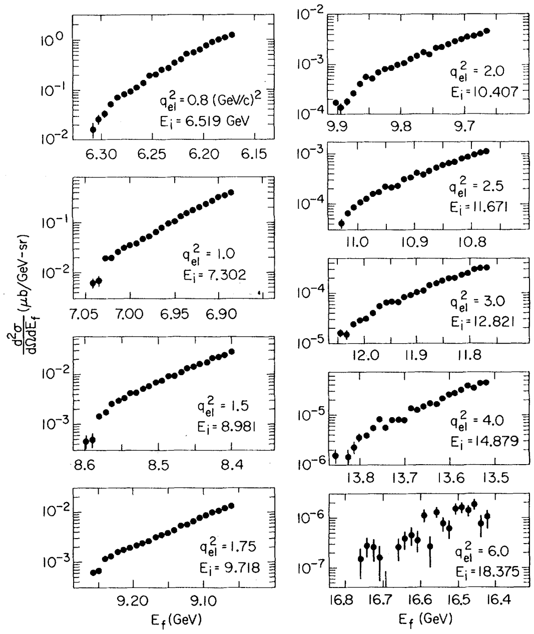

FIG. 2. Inelastic cross sections vs final electron energy. The incident energy is E_i; and q_{el}^2 is the q^2 at the elastic peak. The q^2 variation per spectrum is $\sim 2.5\%$.

The 20-GeV/c spectrometer with 5% momentum acceptance was set to cover the region in Δp between $-0.03 \leq \Delta p/p_e \leq +0.02$. Events from the electron arm were logged when a coincidence signal in three scintillator trigger counters and a large pulse height in a lead-glass and lead-Lucite shower counter was registered. Thus, simultaneously with the double-arm elastic events, we recorded single-arm events from inelastic processes in the threshold region.

Five planes of multiwire proportional chambers recorded the particle trajectory at the spectrometer exit. The angle and momentum of the particles leaving the target were reconstructed using the well-known optical properties of the spectrometer.

The inelastic events are obtained by subtracting empty-target background and elastic scattering events from the electron spectrum. The elastic spectrum is obtained from the double-arm coincidence data scaled up by a factor for the mismatch in solid angle between the double-arm and single-arm systems. The ratio of the total number of events to empty-target background events is ~ 6 at $\Delta p/p_{el} = 0$ and increases to ~ 8 for $\Delta p/p_{el} \leq -1\%$. The finite resolution caused by the initial electron-beam momentum spread is roughly 0.5% (full width at half-maximum) of p_e and given by the width of the elastic peak.

Figure 1 shows the kinematic region of our nine spectra on a q^2-ν plane. The dotted line indicates the experimental limit at 2.3% of p_e below the center of the elastic peak. The pion threshold is always inside the spectra, and the center of the quasielastic peak is always outside the spectra.

For radiative unfolding, we used a method suggested by Crannell[2] using the radiative-correction formulas given by Tsai.[3] This gave an enhancement to the spectra of typically a factor of 1.8 with very little energy dependency. The solid angle $\Delta\Omega$ was determined in a Monte Carlo simulation. Experimental corrections were applied for dead-time losses (5 to 10%) and for wire-chamber track inefficiencies (10%).

Our results for the inelastic cross sections $d^2\sigma/d\Omega\, dE_f$ versus E_f are presented in Fig. 2. The error bars on the data points represent the statistical errors only. The systematical errors, mainly from uncertainties in $\Delta\Omega$ and the corrections, are estimated to $\pm 20\%$. The spectra rise almost exponentially with decreasing E_f, with a sharp rise from zero at the threshold.

In one-photon-exchange approximation, the cross section can be written as

$$\frac{d^2\sigma}{d\Omega\, dE_f} = \frac{\sigma_M}{\nu}\left[\nu W_2(q^2,\nu) + \nu W_1(q^2,\nu)\, 2\tan^2(\tfrac{1}{2}\theta_e)\right],$$

where σ_M is the Mott cross section, and W_1 and W_2 are the deuteron inelastic structure functions,

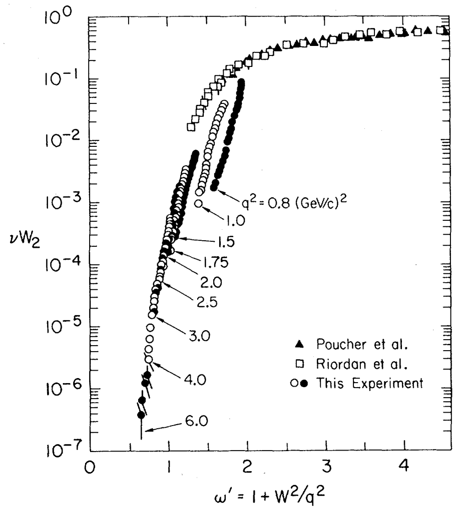

FIG. 3. Our data compared with results from Refs. 5 [$\theta = 6°, 10°$; $W > 2$ GeV; $q^2 > 1$ (GeV/c)^2] and 7 [$\theta = 18°$, $26°, 34°$; $W \geq 2$ GeV; $q^2 \geq 4$ (GeV/c)^2]. The points from our data are from the straight portions of the curves in Fig. 2 above the initial rise at threshold. For clarity, only fewer representative points, which lie on a straight line drawn through the data in Fig. 2, have been plotted for $q^2 = 4$ and 6.

depending on the Lorentz invariants q^2 and ν. Formulas connecting W_1 and W_2 are given, e.g., by Stein *et al.*[4] Assuming $R = 0.18$,[5] we find for our case,

$$\nu W_1 \tan^2(\tfrac{1}{2}\theta_e)/\nu W_2 \leq 0.011,$$

which means that we are practically only sensitive to νW_2.

A preliminary nuclear-physics calculation has been performed using the Reid soft-core potential for the ground state and $^1S_0$ phase shift, together with the remaining plane-wave components for the final state. Only the lowest-order terms in a q^2/M_p^2 expansion were retained because of the large magnitude of that ratio. Thus, there are only charge terms and no magnetic terms. With this severe limitation, this calculation gives a qualitative fit to the $q^2 = 0.8$ and 1.0 (GeV/c)^2 spectra, but underestimates the threshold enhancement. At larger q^2, the calculation overestimates the measured cross section, e.g., at $q^2 = 1.75$ (GeV/c)^2, it is about a factor of 2 higher.[6]

For $Q^2, \nu \to \infty$, it is observed that νW_2 becomes an approximate function of the scaling variable ω' only, with $\omega' = 1 + W^2/q^2$ and $W^2 = M^2 + 2M\nu - q^2$, the square of the missing mass. Figure 3 shows a comparison of our data with data from Poucher *et al.*[5] and Riordan[7] on a νW_2-vs-ω' plot.[8] At q^2 below 2 (GeV/c)^2, we are not yet in the scaling region, but at $q^2 \geq 2$ (GeV/c)^2, our spectra merge with increasing q^2 into a universal $\nu W_2(\omega')$ curve. We find empirically that the spectra with $q^2 \geq 2$ (GeV/c)^2 can be described by the relation $\nu W_2 \sim (\omega' - 0.5)^n$, with $n = 6 \pm 0.5$ for ω' in the region 0.7 to 1.1.[9]

To examine the high-energy features of the deuteron's electromagnetic structure functions and the connection between threshold inelastic and elastic scattering, we have tested the data with the following two predictions. Note that the inelastic data are in a kinematic region inaccessible to the proton.[8]

A connection between the elastic form factor F and W_2 near threshold has been given by Drell and Yan[10] and by West[11] for the case of the proton:

$$\nu W_2 \sim x(1-x)^p, \quad F \sim (1/q^2)^{(p+1)/2},$$

$$x = q^2/2M\nu \to 1.$$

If we extend this prediction to the deuteron, we postulate $p = 9$, since F_d appears to be approaching $(1/q^2)^5$. From our data, we could not get a reasonable fit within $4 \leq p \leq 11$. Therefore, we do not have any evidence that this connection works for the deuteron. However, we seem to be at too small q^2, ν values to observe scaling in x, i.e., one expects the Drell-Yan-West relation to be valid for large W (> 2 GeV) where the full inclusive state is present.

A parton-model analysis of the threshold region for the reaction $eA \to e'X$ provides continuity at the limit $x \to 1$, with the prediction[12]

$$d\sigma/dq^2\,dW^2 = (d\sigma/dq^2)_{\text{elastic}}\rho(W^2) \tag{1}$$

or

$$W_2 = 2MF_d^2(q^2)\rho(W^2), \tag{2}$$

where M is the target mass for nucleus A.

It has been shown that dimensional scaling is satisfied as predicted for the elastic data for $q^2 \gtrsim 0.7$ (GeV/c)^2 by the reduced deuteron form factor, $f_d \equiv F_d/F_N(\tfrac{1}{4}q^2)$, i.e.,

$$q^2 f_d \to \text{const}, \tag{3}$$

and that

$$F_d \sim F_p(\tfrac{1}{4}q^2)(1 + q^2/\tfrac{6}{5}m^2)^{-1}. \tag{4}$$

Furthermore, the normalization in Eq. (4) can be obtained by requiring consistency with the observed large-t falloff of p-p elastic scattering at

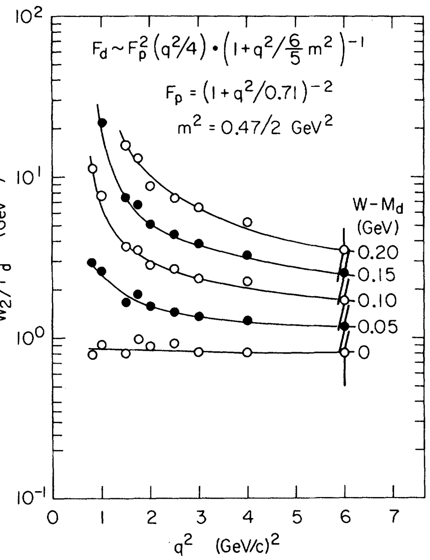

FIG. 4. Inelastic structure function W_2 divided by the square of the deuteron elastic form factor as in Eq. (2). The lines are visual fits.

fixed angle.[12]

The inelastic to elastic structure function ratio $W_2/F_d^{\,2}$ at fixed invariant mass is presented in Fig. 4. F_d from Eq. (4) rather than from the elastic data is plotted so that the ratio can be extended to $q^2 = 6$ (GeV/c)^2 where the measurement of $F_d^{\,2}$ is an upper limit. One observes that the ratio in Fig. 4 factorizes into a function of W and a mild q^2 dependency for $W - M_d \gtrsim 50$ MeV. The main point here is that Eq. (1) accounts approximately for the six-orders-of-magnitude variation in q^2 of W_2 at threshold for $0.6 < x < 0.9$ as observed in Fig. 4. At $x \simeq 1$, i.e., $W - M_d = 0$, the elastic-inelastic connection [Eq. (1)] is satisfied.[13]

If $G(q^2)$ is the excitation form factor of a resonance at $M = M_R$, then

$$\nu W_2 = (M_R^{\,2} - M_d^{\,2} + q^2)[G(q^2)]^2 \delta(W^2 - M_R^{\,2}) \qquad (5)$$

is its contribution to νW_2 in the narrow-resonance approximation.[14] Our data indicate that this relation works in our case ($M_R \approx M_d$), i.e., $\nu W_2 \sim q^2 F_d^{\,2} \rho(W^2)$, as in Eq. (2). Thus, our measurements indicate that νW_2 at threshold behaves like a resonance with $G(q^2) \sim F_d(q^2)$. This leads, in the language of the quark model, to the conclusion that, as in the elastic case, all six quarks participate in the threshold inelastic scattering process.

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