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ELECTROPRODUCTION OF HADRONS FROM DEUTERIUM*

J. T. Dakin, G. J. Feldman,
F. Martin, M. L. Perl and W. T. Toner†

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

The inclusive electroproduction of hadrons is measured from hydrogen and deuterium targets. The exchanged virtual photons are in the kinematic range $-0.25 > q^2 > -3.00$ GeV^2, $12 < s < 30$ GeV^2. Hadrons which travel in the direction of the virtual photon in the virtual photon-nucleon center-of-mass system are detected. A striking difference from photoproduction is observed in the excess of positive relative to negative hadrons from both proton and neutron targets.

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†Present address: Rutherford High Energy Laboratory, Chilton, Didcot, Berkshire, England.

Electron-nucleon scattering is commonly interpreted as a process in which an electron scatters by imparting four-momentum to a virtual photon (γ^*) which in turn interacts with the nucleon. In a previous letter[1] we reported on the inclusive production of hadrons (h) in γ^*-proton collisions:

$$\gamma^* p \rightarrow h^{\pm} + \text{anything} \quad . \tag{1}$$

In this letter we report the result of a similar measurement with a deuterium target, and the extraction of results for a neutron target:

$$\gamma^* n \rightarrow h^{\pm} + \text{anything} \quad . \tag{2}$$

The γ^* is characterized by two kinematic variables — q^2, its four-momentum squared; and s, the c.m. energy squared in the γ^*-nucleon collision. The total γ^*-nucleon cross section is denoted σ_{tot}.[2] Cross sections for (1) and (2) are parametrized with three inclusive variables relative to the γ^* direction — ϕ, the azimuthal angle; $p_\perp^2$, the transverse momentum squared; and x the longitudinal momentum in the γ^*-nucleon c.m. frame divided by its largest possible value.

The apparatus has been described elsewhere.[1,3] It consisted of a 19.5 GeV/c electron beam, a target which was filled sometimes with liquid hydrogen (H_2) and sometimes with liquid deuterium (D_2), and a large-aperture magnetic spectrometer. The optical spark chambers were pulsed and photographed whenever a scattered electron of greater than 4 GeV energy was detected by an array of lead-lucite shower counters. A picture then contained the trajectory of the triggering electron along with those of any accompanying hadrons of lab momentum greater than 2 GeV, and in the polar angular region $30 < \theta < 300$ mrad.

We photographed 250,000 events with the H_2 target and 110,000 events with the D_2 target. All pictures were scanned and measured with a flying-spot digitizer to find the trajectories of the electrons and hadrons. A trajectory was interpreted as an electron if its negative momentum was consistent with the pulse height in the shower counter through which it passed. We limited the kinematic region of interest to $-.25 > q^2 > -3.0$ GeV^2, and $12 < s < 30$ GeV^2. There we found 30,401 electrons from H_2 and 14,772 from D_2. These electrons were divided into 16 bins in the q^2-s plane, and the number in each bin was taken to represent the total number of γ^*-p or γ^*-d interactions, effectively $\sigma_{tot}(q^2, s)$. These numbers were corrected bin-by-bin for geometric acceptance, scanning and measuring losses ($\sim 25\%$), radiative effects ($\sim 25\%$) and hadron contamination ($\sim 3\%$).

Trajectories which were in-time with the triggering electron, as indicated by a scintillation hodoscope, but which made negligible pulse-heights in the shower counter hodoscope were interpreted as hadrons. For the purpose of kinematic computations these were all assumed to be π's. Events were selected having both an electron in the above q^2-s range, and a hadron in the range $0 < \phi < 2\pi$, $p_\perp^2 < 0.7$ GeV^2 and $x > 0.1$. Of the inclusive hadronic events of this type there were 9250 from H_2 and 4663 from D_2. The losses in the number of electron-hadron events due to scanning and measuring inefficiency depended only slightly on hadron charge and on target type, and were typically $\sim 45\%$. The scanning and measuring efficiencies and their possible biases were studied by an independent measurement of 28,000 frames of H_2 data and 47,000 frames of D_2 data with a repetitive manual system.

Cross sections were determined for reactions (1) and (2) by first fitting the hadron-electron events with a maximum-likelihood technique to the form

$$\frac{1}{\sigma_{tot}(q^2, s)} \frac{d\sigma(q^2, s)}{dx\, dp_\perp^2\, d\phi} = \frac{dN}{dx}\, b e^{-bp_\perp^2} \frac{(1 + A \cos \phi + B \cos 2\phi)}{2\pi} \qquad (3)$$

The fitting function contained the normalization, $\sigma_{tot}(q^2, s)$, determined from counting electrons, the detailed dependence of the geometric efficiency on the variables ϕ, $p_\perp^2$, x, hadron charge, s and q^2, and the dependence of the scanning-measuring efficiency on hadron charge and target type. Fits were always done separately for H_2 and for D_2, for positive and negative hadrons, and for small intervals of x. The outputs of the fits included the differential multiplicities, dN/dx, the transverse momentum slope parameters, b, and the azimuthal asymmetries, A and B. The latter were always consistent with 0, and with 90% confidence never greater than 0.3. The data described in the remainder of this Letter are from fits in which A and B are fixed at 0.

The slope parameters, b, are shown in Fig. 1 for two different x regions as a function of q^2. In the high x region the b's tend to decrease with increasing $|q^2|$. The slopes from H_2 and D_2 are the same within statistics.

The x-distributions for reaction (1) were reported earlier.[1] These distributions as well as those from D_2 are similar in shape to the distributions for inclusive π's in photoproduction,[4] provided that decay-π's from the reaction $\gamma p \rightarrow \rho^o p$ are removed. The $\rho^o p$ final state is known to be a smaller fraction of the total cross section as $|q^2|$ increases,[3] however this effect is too small to account for the asymmetry to be discussed next.

The most dramatic effect in reaction (1) is the growing excess of positive relative to negative hadrons as $|q^2|$ increases. This effect is demonstrated in Fig. 2a where N^+/N^- is plotted versus q^2. Here $N^+(N^-)$ represents for positive (negative) hadrons the integral of dN/dx over $0.4 < x < 0.85$. The region $.85 < x < 1.0$ is eliminated to explicitly exclude the contributions of the exclusive channels $\gamma^* p \rightarrow \pi^+ n$ and $\gamma^* p \rightarrow \pi^\pm N^*(1238)$, although this contribution is negligible for our s range. The h^+-h^- asymmetry is greater for $x > 0.4$ than for $0.1 < x < 0.4$.[1]

Also shown in Fig. 2a are the charge ratios for reaction (1) and the same x range extracted from other experiments.[5-9] All of the other experiments have π-k-p separation, and the results shown are explicitly the π^+/π^- ratios. We have concluded from the q^2 and s dependence of the inclusive k's and p's in one of these experiments[8] that the hadrons reported here are predominantly π's.

The central purpose of this Letter is to extend the above charge ratio measurement for reaction (1) to one for reaction (2). To do this required a deuterium subtraction, to be discussed next. The principal assumption which we made was that the cross section for an inclusive process from deuterium,

$$\gamma^* d \to h^{\pm} + \text{anything} \quad , \tag{4}$$

is simply the sum of the corresponding cross sections for reactions (1) and (2). This assumption is justified by the observations that in this q^2-s range (1) there is no evidence for "shadowing" in measurements of σ_{tot} for heavy nuclei,[2] (2) the deuterium "smearing" corrections to σ_{tot} are negligible,[10] and (3) we see no evidence for coherent production from D_2 in the transverse momentum slopes.

Because our cross sections were in the form of differential multiplicities, internally normalized to the σ_{tot}'s, we subtracted them with the formula

$$\frac{dN}{dx_n} = \frac{\sigma^d_{tot}}{\sigma^n_{tot}} \frac{dN}{dx_d} - \frac{\sigma^p_{tot}}{\sigma^n_{tot}} \frac{dN}{dx_p} \quad . \tag{5}$$

The subtraction was done in separate x bins, and separate regions of the q^2-s plane. The ratios σ^d_{tot}/d^n_{tot} and $\sigma^p_{tot}/\sigma^n_{tot}$ depended on q^2 and s and were extracted from the literature.[10] Corrections were made for the target-empty events (4% of the D_2 events), and for a 3% H_2 contamination in the D_2.

The charge ratio extracted for the neutron is shown in Fig. 2b. The errors shown represent statistical uncertainty only. There may be additional systematic errors no larger than ±20% of the value of the charge ratio, due to uncertainty in the scanning and measuring efficiency. Included in Fig. 2 are charge ratios from photoproduction at s = 14.9.[5] There it has been noted that the following isospin symmetry holds for the π^+/π^- charge ratios:

$$\left(\frac{N^+}{N^-}\right)^p \approx \left(\frac{N^-}{N^+}\right)^n \approx 1.2 \qquad (6)$$

In electroproduction we have found the charge ratios very much different. First, we observe a striking hadron charge asymmetry from the p target, with $N^+/N^- \approx 2$ at $q^2 \approx -1\ \mathrm{GeV}^2$. Second, the isospin symmetry of Eq. (6) clearly breaks down, there appearing to be more h^+ than h^- from the n target also. These changes in the hadron composition occur in the kinematic region $0.4 < x < 0.85$, a region populated by the decay products or fragments of the γ^* in any diffractive model of γ^*-nucleon interactions. Since the γ^* is neutral, the charge asymmetries in electroproduction make any such diffractive model less attractive than in nearly-symmetric photoproduction. The above changes from the charge and isospin symmetric hadrons of photoproduction to the asymmetric hadrons of electroproduction take place in the q^2 range in which scaling begins.[2]

We wish to point out that the behavior shown in Fig. 2 has a natural explanation in a quark-parton model. In such a model the γ^* strikes p-type $\left(\text{charge} + \frac{2}{3}\right)$ valence quarks in preference to n-type $\left(\text{charge} - \frac{1}{3}\right)$ valence quarks. These struck quarks fragment in the γ^* fragmentation region, the p-type preferentially to π^+, the n-type preferentially to π^-. This gives a net π^+ excess for the proton, and a smaller π^+ excess for the neutron. This model gives a testable prediction[11] for the pion multiplicities in our x range:

$$R = \frac{\int_1^\infty \left(N_n^+ - N_n^-\right) F_1^n(\omega)\, \frac{d\omega}{\omega^2}}{\int_1^\infty \left(N_p^+ - N_p^-\right) F_1^p(\omega)\, \frac{d\omega}{\omega^2}} = \frac{2}{7} = .29 \qquad (7)$$

Here ω is the scaling variable, $\omega = \left(q^2 + M^2 - s\right)/q^2$, $F_1(\omega)$ is a known inelastic structure function, and p and n represent the proton and neutron. We are able to test this prediction with our data only over the limited range $3 < \omega < 60$, and here compute the value $R = .24 \pm .28$. Clearly a more precise test of relation (7) is needed. A more detailed discussion of these results in relation to the quark-parton model is reported separately.[12]

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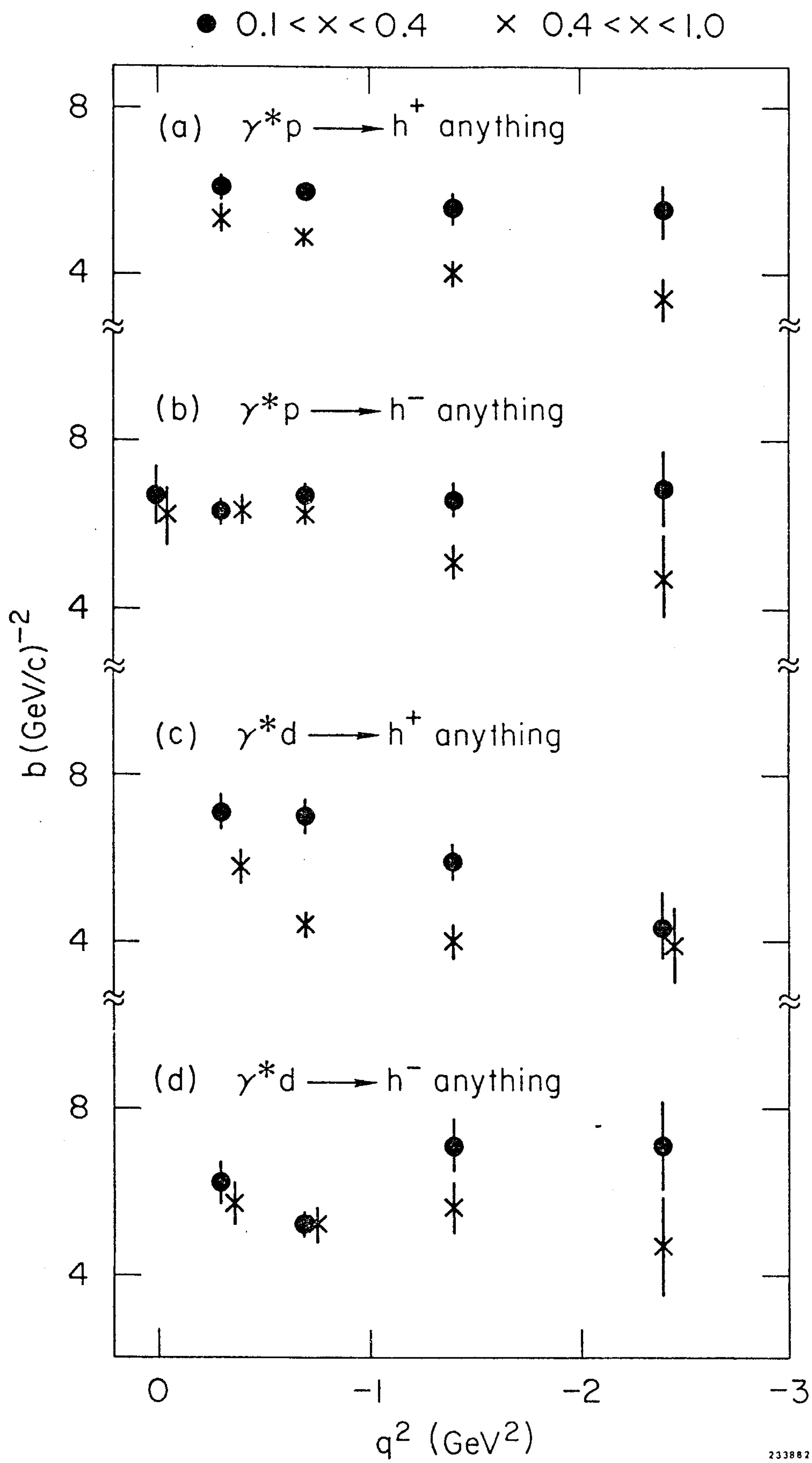
FIGURE CAPTIONS

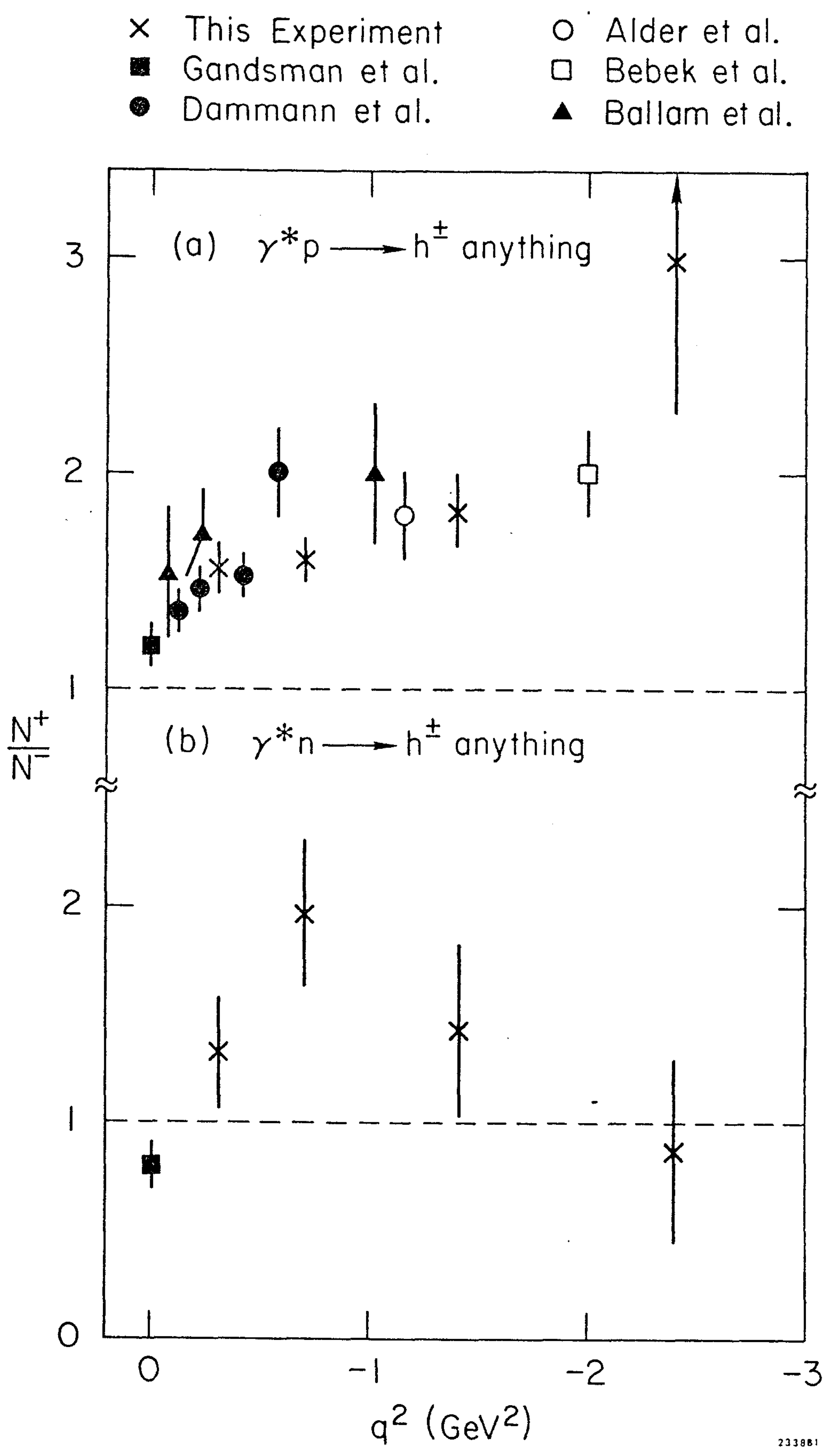
1. Slope parameters describing the $p_\perp^2$ distributions for (a) h^+ from hydrogen, (b) h^- from hydrogen, (c) h^+ from deuterium, and (d) h^- from deuterium. The points at $q^2=0$ are from fits to photoproduction data at $s = 18.3$ GeV^2.[4]

2. Ratios of the positive hadron to negative hadron multiplicity in the range $0.4 < x < 0.85$ for (a) proton target and (b) neutron target. The s ranges of the data from the experiments are Gandsman *et al.*[5] (14.9 GeV^2), Dammann *et al.*[6] (7 GeV^2), Alder *et al.*[7] (7 GeV^2), Bebek *et al.*[8] (7 GeV^2), Ballam *et al.*[9] (6-25 GeV^2), and this experiment (12-30 GeV^2).



● 0.1 < x < 0.4
× 0.4 < x < 1.0
(a) γ*p ⟶ h⁺ anything
(b) γ*p ⟶ h⁻ anything
(c) γ*d ⟶ h⁺ anything
(d) γ*d ⟶ h⁻ anything
b (GeV/c)⁻²
8
4
8
4
8
4
8
4
0
−1
−2
−3
q² (GeV²)
233882

Fig. 1



× This Experiment
■ Gandsman et al.
● Dammann et al.
○ Alder et al.
□ Bebek et al.
▲ Ballam et al.
(a) γ*p ⟶ h± anything
(b) γ*n ⟶ h± anything
N+/N−
q² (GeV²)
0
1
2
3
0
−1
−2
−3
233881

Fig. 2