Inclusive Electroproduction of Forward Protons from Neutron and Proton Targets*

C. J. Bebek, C. N. Brown,† M. Herzlinger, S. Holmes, C. A. Lichtenstein,‡
F. M. Pipkin, S. Raither, and L. K. Sisterson§
Cyclotron Laboratory, Harvard University, Cambridge, Massachusetts 02138
(Received 10 February 1975)

We report new measurements of the inclusive electroproduction of forward protons carried out at the Wilson Synchrotron Laboratory at Cornell University. Data were taken with deuterium at the (W, Q^2) points (2.15 GeV, 1.2 GeV^2), (2.15, 4.0), and (3.11, 1.2); data were taken with hydrogen at these points and at the points (2.15, 2.0), (2.67, 3.3), and (3.11, 1.7). The invariant structure function is presented in terms of W, Q^2, and $\boldsymbol{\omega}$.

The large cross section for deep-inelastic electron-nucleon scattering, which is a function of a single variable $\omega = 2M\nu/Q^2$, has aroused considerable theoretical and experimental interest in the details of the processes which are responsible for it. One particularly interesting feature is the decrease in the scattering from the neutron relative to that from the proton as ω decreases. This paper reports the first measurements from both neutron and proton targets in which a proton moving in approximately the same direction as the virtual photon is observed.

In what is now standard notation, electroproduction can be treated as photoproduction by a virtual photon, where the square of the photon mass Q^2, energy ν, direction, and polarization parameter ϵ are tagged by the scattered electron. We present the virtual-photon–target-nucleon cross sections in terms of the same kinematic variables which were defined and used in Bebek *et al.*[1] Instead of differential cross sections, we show the invariant structure function

$$F = \frac{E}{\sigma_{\text{tot}}}\frac{d^3\sigma}{dp^3} = \frac{1}{\sigma_{\text{tot}}}\frac{1}{\pi}\frac{E^*}{[p_{\text{max}}^{*2} - p_\perp^2]^{1/2}}\frac{d\sigma}{dx'dp_\perp^2}, \quad (1)$$

where σ_{tot} is the total virtual-photoproduction cross section for the W and Q^2 of the reaction. For the proton target, the value of σ_{tot} was taken from a fit to the electron scattering measurements of νW_2 with the assumption that $\sigma_S/\sigma_T = 0.18$.[2] For the neutron target, the value of σ_{tot} was computed from the empirical relation[3]

$$\sigma_n/\sigma_p = (1 - 0.75/\omega). \quad (2)$$

The scattered electron was detected in one magnetic spectrometer; the electroproduced hadron was detected in a second magnetic spectrometer. A combination of a Cherenkov counter and a lead-Lucite shower counter identified electrons. Pions were identified by a threshold gas Cherenkov counter when their momenta were ≥ 1.8 GeV/c and by their time of flight when their momenta were < 1.8 GeV/c. Neither protons nor kaons gave a signal in the Cherenkov counter, so protons were separated from kaons entirely by their time of flight.

Data were taken at the points in the (Q^2, ν) plane shown in Fig. 1. Hydrogen data were taken for all the points; deuterium data were taken at data points 8, 9, and 13. The measured cross sections were corrected for random coincidences (~5%), for counter and spark-chamber dead time (~5%), for nuclear absorption (2–3%), and for target-wall background (~5%). No radiative corrections have been applied to the data shown in the graphs. The errors quoted are statistical; there is an additional overall systematic uncertainty which is estimated to be less than 10%.

A simple correction for smearing was used to determine the cross sections for a neutron target from the deuterium data. The neutrons were assumed to be on the mass shell and have a momentum distribution given by the Hulthén momentum-space wave function.[4] This momentum distribution was used to calculate, from the measured structure function for protons from a proton target F_p, a smeared proton structure function F_p^s. For $-0.6 \leq x' < 0.0$, the correction due to smearing, $C = F_p/F_p^s$, differed from unity by less than 5%; for $0.0 \leq x' < 1.0$, it differed from unity by less than 3%. The expression

$$F_n = \left[\frac{E}{\sigma_p}\frac{d^3\sigma}{dp^3}\bigg|_{\text{D}} C - \frac{E}{\sigma_p}\frac{d^3\sigma}{dp^3}\bigg|_{\text{H}}\right]\left(\frac{\sigma_p}{\sigma_n}\right) \quad (3)$$

was used to calculate, from the deuterium data, the unsmeared structure function for protons from a neutron target. This procedure assumes that the deuterium cross section is the simple sum of the neutron and proton cross sections. The smearing correction for νW_2 is small for the

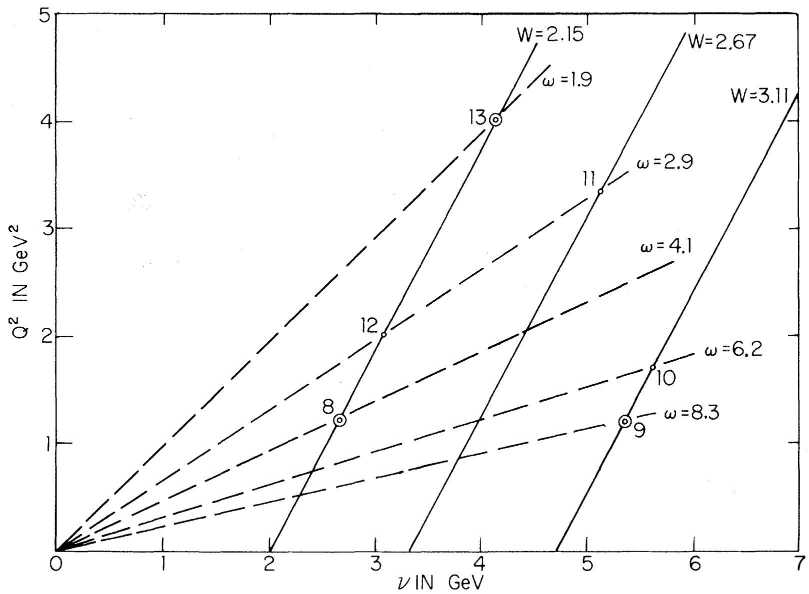

FIG. 1. Q^2, ν points at which data were taken. The circles indicate points at which deuterium data were taken.

ω region of this experiment.[5,6]

Figure 2(a) shows the invariant structure function for protons from a proton target for $p_\perp^2 < 0.02$ GeV^2 for two points with the same center-of-mass energy W and different Q^2. The data indicate that at fixed W the invariant structure function is not a strong function of Q^2. This agrees with previous observations.[7,8]

Figure 2(b) shows the invariant structure function for protons from a proton target for two points with the same Q^2 and different center-of-mass energies W. This shows the rapid decrease with energy of the invariant structure function for forward-going protons.

Figure 2(c) shows on the same graph the invariant structure function for protons from a neutron

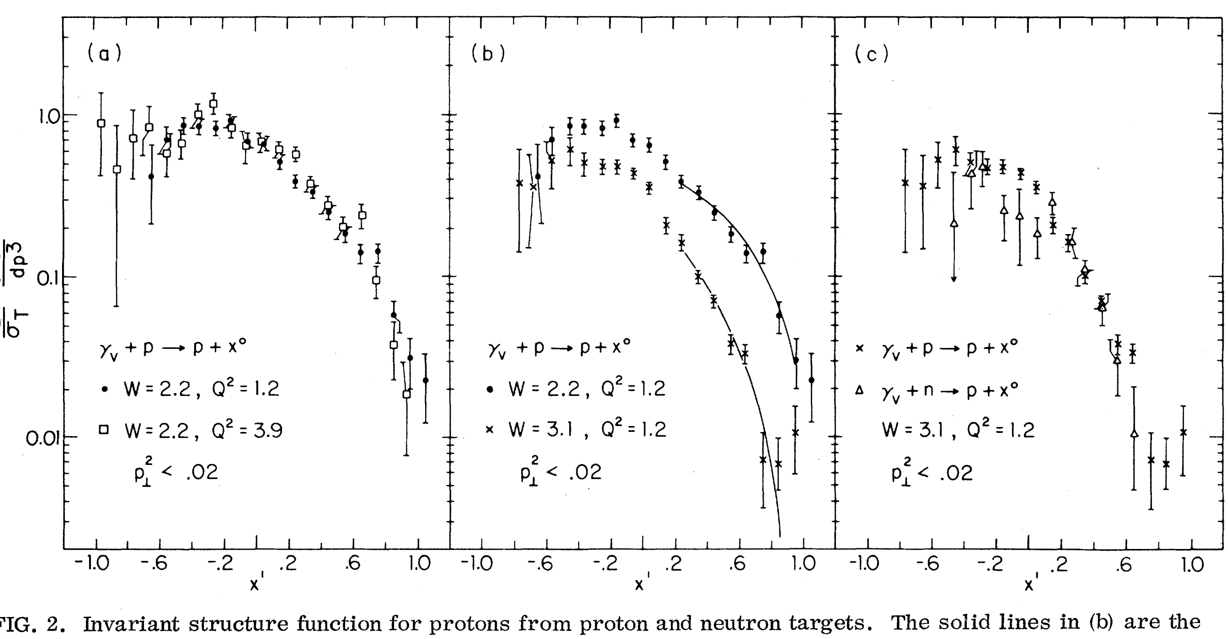

FIG. 2. Invariant structure function for protons from proton and neutron targets. The solid lines in (b) are the curves for a fit of the form $A(1-x')^n$.

TABLE I. The average ratio of the structure function for forward protons from a neutron target to that for forward protons from a proton target for protons with $0.1 \leq x' < 1.0$ and $p_\perp^2 < 0.02$. The uncertainties are statistical only. The systematic errors tend to cancel in this ratio and are estimated to be less than 5%.

Datum point	W, Q^2 (GeV, GeV^2)	$1/\omega$	n/p
9	3.11, 1.2	0.12	0.82± 0.19
8	2.15, 1.2	0.24	0.85± 0.13
13	2.15, 4.0	0.47	0.82± 0.44

target and for protons from a proton target for $p_\perp^2 < 0.02$ GeV^2. Table I summarizes the average ratios of the structure functions for $0.2 \leq x' < 1.0$ for forward protons from neutron and proton targets for the points at which deuterium data were taken. The data indicate that the relative probability of obtaining a forward proton from a neutron target is essentially the same as that for obtaining a forward proton from a proton target and that the ratio of the probabilities is not a strong function of ω.

Data obtained out to $p_\perp^2 = 0.3$ GeV^2 showed the same behavior for the invariant structure function. For data points 8, 12, and 13, where $W = 2.15$ GeV, the slope parameters B in a fit of the form $A \exp(-Bp_\perp^2)$ for $0.6 \leq x' < 1.0$ were 4.0± 1.0, 7.1± 0.8, and 3.9± 1.3 GeV^{-2}, respectively. The corresponding slope parameters for data points 9 and 10, where $W = 3.11$ GeV, were 3.3± 0.7 and 2.1± 1.0 GeV^{-2}, respectively. The $p_\perp^2$ data for the neutron target gave slope parameters consistent with the values for the proton target.

In order to compare the data with theoretical predictions, the invariant structure function for $0.2 \leq x' < 1.0$ was fitted by the expression

$$F(x') = A(1-x')^n. \tag{4}$$

In Reggeized models of inclusive reactions n is related to the intercept of the leading Regge trajectory through the expression

$$n = 1 - 2\alpha(0). \tag{5}$$

The value $n = 2$ or its equivalent $\alpha(0) = -\frac{1}{2}$ corresponds to Reggeized baryon exchange. This behavior was first suggested by Feynman[9]; it is a consequence of the correspondence-principle arguments of Bjorken and Kogut[10] and the more general analysis of Mueller.[11] The solid curves in Fig. 2(b) are representative of the fits to Eq. (4). Figures 3(a) and 3(b) show the value of n as a

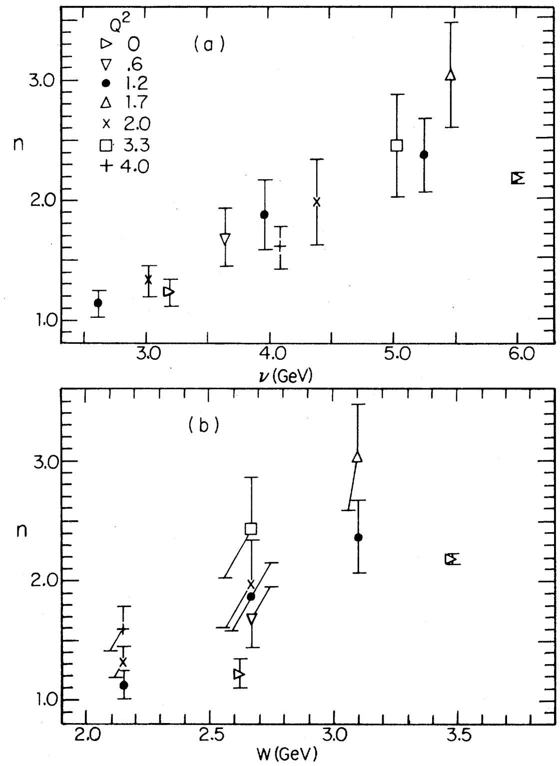

FIG. 3. The exponent n in a fit of the form $A(1-x')^n$ to the invariant structure function for protons from a proton target with $0.2 \leq x' < 1.0$ and $p_\perp^2 < 0.02$, (a) as a function of ν, (b) as a function of W.

function of ν and W, respectively. Also shown in Fig. 3 is the value of n determined in two photoproduction experiments.[12,13] The data are not inconsistent with n increasing linearly with ν and then becoming constant at $n = 2$.

It seems remarkable that the relative probability of obtaining a forward proton from a neutron target is nearly the same as that from a proton target, independent of Q^2, W, and ω. The structure function for forward protons shows a W dependence characteristic of Reggeized baryon exchange and only a weak Q^2 dependence. The scaling in ω predicted by simple parton models has not been observed.

We wish to acknowledge the support of Professor Boyce McDaniel, the staff of the Wilson Synchrotron Laboratory, and the Staff of the Harvard Cyclotron Laboratory. We would like to thank the Electron Scattering Group at Cornell for the loan of their spectrometer.

*Research supported in part by the U. S. Atomic En-

ergy Commission under Contract No. AT(11-1)-3064.

†Present address: Fermi National Accelerator Laboratory, P. O. Box 500, Batavia, Ill. 60510.

‡Present address: P. O. Box 29246, Los Angeles, Calif. 90029.

§Present address: 36 Webb St., Lexington, Me. 02173.

[1]C. J. Bebek et al., Phys. Rev. Lett. 30, 624 (1973).
[2]W. B. Atwood, private communication.
[3]A. Bodek et al., Phys. Rev. Lett. 30, 1087 (1973).
[4]L. Hulthén and M. Sugawara, in *Handbuch der Physik*, edited by S. Flügge (Springer, Berlin, 1957), Vol. 39, p. 1.
[5]W. B. Atwood and G. B. West, Phys. Rev. D 7, 773 (1973).
[6]G. B. West, Ann. Phys. (New York) 74, 464 (1972).
[7]J. C. Adler et al., Nucl. Phys. B46, 415 (1972).
[8]C. J. Bebek et al., Phys. Rev. Lett. 32, 27 (1974).
[9]R. P. Feynman, Phys. Rev. Lett. 23, 1415 (1969).
[10]J. D. Bjorken and J. Kogut, Phys. Rev. D 8, 1341 (1973).
[11]A. H. Mueller, Phys. Rev. D 2, 2963 (1970).
[12]H. Burfeindt et al., Phys. Lett. 43B, 345 (1973).
[13]H. Burfeindt et al., Nucl. Phys. B74, 189 (1974).

Search for Charmed-Particle Production in 15-BeV/c π^+p Interactions*

C. Baltay, C. V. Cautis, D. Cohen, S. Csorna,† M. Kalelkar, D. Pisello, and E. Schmidt
Columbia University, New York, New York 10027

and

W. D. Smith and N. Yeh
State University of New York at Binghamton, Binghamton, New York 13901

A search for the production of charmed particles in 15-BeV/c π^+p interactions has been carried out. The search was sensitive to charmed particles in the 1.5 to 4.0 BeV mass range, with lifetimes $\lesssim 10^{-11}$ sec, decaying into a strange particle with up to eight additional pions. No evidence for the production of such particles was found.

The possibility of a new hadronic quantum number, charm, which had been suggested about ten years ago,[1] has recently received renewed attention.[2,3] In the simple quark model of the hadrons, this hypothesis can be interpreted as the existence of a fourth quark c carrying one unit of charm, in addition to the usual nonstrange quarks u and d, and the strange quark s. In order to be useful in canceling the strangeness-changing neutral currents, the c quark must have the same charge as the $I_z = +\frac{1}{2}$ u quark, and have weak couplings to the d and s quarks which are proportional to $\sin\theta$ and $\cos\theta$, respectively, where θ is the Cabibbo angle. The lowest-mass charmed baryons and mesons would thus be expected to decay predominantly into final states containing a strange particle. If charm is conserved in the strong interactions, then charmed particles would be produced in association with other charmed particles in strong processes.

We have carried out a systematic search for the production of charmed particles in π^+p interactions by looking for specific associated-production processes, as well as for inclusive-production processes, followed by the decay of the charmed particles into strange particles and pions. The distance traveled by the charmed particles before decay was assumed to be too short to be visible. The signal for the production and decay of such a particle would have been the accumulation of events at the mass of the particle in the effective-mass distribution of its decay products. The search was thus sensitive to new particles with lifetimes $\lesssim 10^{-11}$ sec. The total energy in the center of mass of the π^+p system, for incident pions with 15-BeV/c laboratory momentum, is 5.4 BeV.

The experiment has been carried out at the Stanford Linear Accelerator Center using an rf separated 15-BeV/c π^+ beam incident on the 82-in. bubble chamber filled with liquid hydrogen. A total of 866 000 pictures were taken and scanned, and all interactions were recorded. All interactions up to the highest multiplicity observed (fourteen outgoing charged tracks), with or without associated neutral-particle decays (vees), were measured on the Columbia University Hough-Powell Device operating in an automatic-pattern-recognition mode. About 750 000 events were measured. The measurements were processed by an event-finding program, followed by three-dimensional geometrical reconstruction and ki-