Coincidence Electroproduction of Single Charged Pions from Deuterium*

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We have studied the electroproduction of single charged pions from deuterium in a coincidence experiment at the Cambridge Electron Accelerator. Data are presented for a virtual-photon mass squared near -0.4 GeV^2 and virtual photoproduction center-of-mass energy and angle near 2.15 GeV and 0°, respectively. The data are used to study the isoscalar-isovector interference and the nuclear-physics corrections arising from the use of a deuterium target.

We have measured the electroproduction of single charged pions from deuterium in a coincidence experiment at the Cambridge Electron Accelerator. A comparison of the charge-symmetric reactions is used to measure the interference between the isovector and isoscalar amplitudes and thus test the assumptions used in theoretical models of pion electroproduction. The ratio of the cross sections for production from the protons in deuterium to that from hydrogen gives a measure of the corrections to single-nucleon cross sections arising from the use of a nuclear target.

To lowest order in quantum electrodynamics the inelastically scattered electrons can be considered a source of tagged, polarized, virtual photons which interact with the nucleons through the reactions[1,2]

$$\gamma^* + p \to \pi^+ + n, \tag{1}$$

$$\gamma^* + d \to \pi^+ + n + n_s, \tag{2}$$

$$\gamma^* + d \to \pi^- + p + p_s. \tag{3}$$

The subscript s denotes the spectator particle which, in the impulse approximation, does not directly participate in the interaction.[3]

We have measured the deuterium cross sections at a virtual-photon mass squared k^2 near -0.4 GeV^2 and a virtual photoproduction center-of-mass energy W near 2.15 GeV. The pions were detected primarily along the virtual-photon direction, corresponding to virtual photoproduction t between -0.01 and -0.08 GeV^2 or pion–virtual-photon angles θ between 0° and 15° in the πN center-of-mass system. The parameter ϵ, which characterizes the virtual-photon polarization density matrix, was between 0.75 and 0.9. Of the transverse components, the one corresponding to photons polarized parallel to the production plane predominated. Earlier measurements have shown that Reaction (1) has a large scalar component not present in photoproduction.[4,5]

As for the previously reported results,[1] a two-arm spectrometer was used to detect the scattered electron and the electroproduced pion. The hadron-arm Cherenkov counter was used to separate pions from protons for Reaction (2) and pions from electrons for Reaction (3). All other event-selection criteria were the same as in Ref. 1.

Each arm had a small horizontal angle acceptance (1°) and a large momentum acceptance (± 30%). Since W, k^2, ϵ, and the laboratory angle of the virtual photon depend on the scattered electron momentum, these variables are strongly correlated. Because of our narrow angular acceptance, for one setting of the apparatus θ is also correlated with W, and the angle φ between the electron-scattering plane and the hadron-production plane is near 0° (180°) for small (large) W.

Figure 1 shows the ratio R of the π^- to π^+ elec-

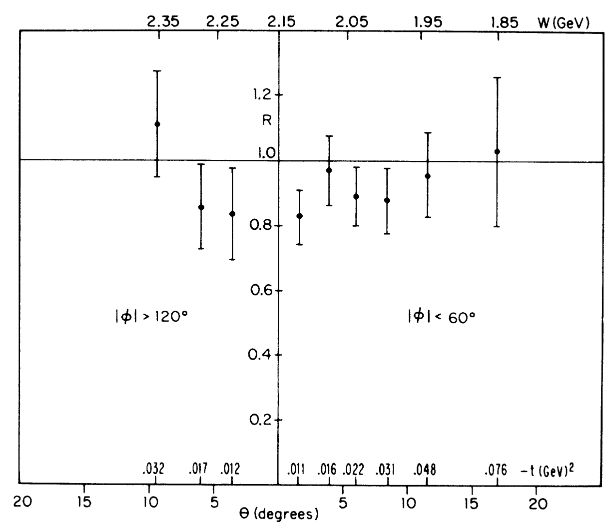

FIG. 1. The measured ratio R of the cross sections for the production of single π^- and π^+ mesons from deuterium. The lower scale shows the momentum transfer and the πN center-of-mass production angle. The upper scale shows the total πN center-of-mass energy.

troproduction cross sections from deuterium plotted against θ with the correlated variation of W and the two regions of φ explicitly shown. The ratio has been corrected to include effects from differences in spark-chamber recovery dead times (7.1%), differences in the radiative correction for the two charge states (≈4%), misidentification of π^+ (2.5%), misidentification of π^- (0.3%), hydrogen contamination in the target (0.7%), and other small effects (≈0.3%). The Coulomb interaction between the final-state protons in Reaction (3) was assumed to be negligible[6,7]; all other nuclear-physics corrections and apparatus effects are expected to cancel.

In terms of the isovector and isoscalar virtual photoproduction amplitudes, this ratio can be written

$$R=\frac{|A_v|^2+|A_s|^2-2\,\mathrm{Re}(A_s{}^*A_v)}{|A_v|^2+|A_s|^2+2\,\mathrm{Re}(A_s{}^*A_v)},$$

$$\approx 1-4\frac{\mathrm{Re}(A_s{}^*A_v)}{|A_v|^2+|A_s|^2}.$$

Using the five central points of Fig. 1 ($\theta \leq 6°$), we obtain for the fractional contribution of the interference term to each cross section

$$\frac{2\,\mathrm{Re}(A_s{}^*A_v)}{|A_v|^2+|A_s|^2}\approx \tfrac{1}{2}(1-R)=0.063\pm 0.025.$$

We note that in photoproduction[8] (1) the ratio of the π^- to π^+ cross sections is nearly independent of energy over a much wider range than that covered by our data; (2) the ratio for photons polarized parallel to the detection plane is consistent with 1.0 for all t; and (3) for the perpendicular polarization the ratio falls from 1.0 at $|t|_{\mathrm{min}}$ to 0.7 at the maximum $-t$ reached by this experiment. Figure 1 shows that R is consistent with 1.0 for $-t \gtrsim 0.032\ \mathrm{GeV}^2$, indicating that the scalar and parallel polarizations do not contain isoscalar terms as large as those seen in the perpendicularly polarized photoproduction measurements. Recent dispersion-theory models of π^+ electroproduction assume that the isoscalar amplitude is zero.[9-11] Fraas and Schildknecht have included an isoscalar-isovector interference term in their calculation, based on the vector-meson-dominance model, of pion electroproduction.[12] They predicted that this term would contribute less than 10% to the cross section for $-t \leq 0.1\ \mathrm{GeV}^2$. Our data are consistent with both of these approaches.

Figure 2 shows the ratio R of the cross sections for π^+ production from deuterium to those

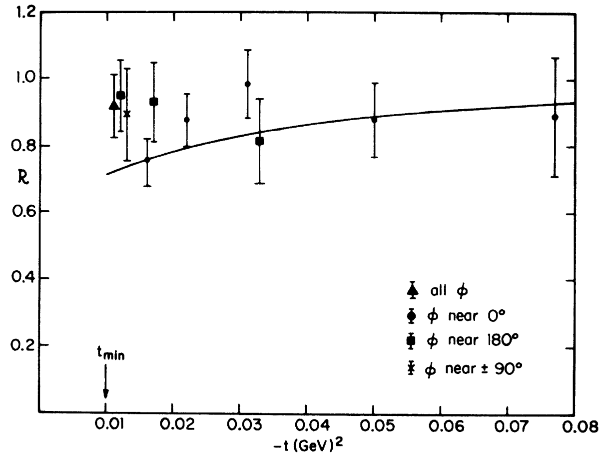

FIG. 2. The ratio of the cross section for the production of single π^+ mesons from deuterium to that from hydrogen. The curve is the theoretical prediction of Dar and Gal modified to take into account the mass of the virtual photon.

for production from hydrogen. Data for the latter reaction have been presented in Ref. 1. The W-φ correlation is not shown explicitly but is the same as in Fig. 1. Corrections have been applied to the ratio for differences in chamber recovery dead times (0.8%), differences in target bremsstrahlung (≈1.5%), and miscellaneous apparatus effects (≈0.5%). A Monte Carlo calculation based on the Hulthén wave function of the deuteron[3] was used to correct for those events kinematically excluded by the data-analysis procedure because of Fermi motion of the target nucleon (≈3%). Corrections have not been made for other deuterium effects.

If the presence of the spectator particle had no effect on the production cross section, this ratio would be 1. Deviations from this value can arise from shadowing of the target nucleon by the spectator (the Glauber correction)[13] and from effects due to the Pauli exclusion principle, which suppresses the cross section by excluding those final states in which the identical nucleons of Reactions (2) and (3) would retain the symmetric ^3S state of the deuteron. Both effects have been calculated by several authors for π^+ photoproduction.[14-18] In particular, Dar and Gal[14] obtain for the deuterium-hydrogen ratio

$$R=1-\beta S(\vec{q}_t)-\frac{(1-\beta)}{4\pi}\langle r^{-2}\rangle_d\,\sigma_{\mathrm{tot}}(\pi^+n). \qquad (4)$$

Here $S(\vec{q}_t)$ is the deuteron form factor with $\vec{q}_t$ the transverse momentum transfer, $\langle r^{-2}\rangle_d$ is the mean inverse squared radius of the deuteron, and $\sigma_{\mathrm{tot}}(\pi^+n)$ is the total cross section for pion absorption by a neutron. β is respectively $\frac{1}{3}$ or 1 when the amplitude is purely spin dependent or spin nondependent. The second term in Eq. (4) allows for the exclusion effect; the third term estimates the Glauber correction.

The Glauber correction results almost entirely from the shadowing of the produced π^+, and so the effect should be the same for electroproduction. However, the photoproduction calculation of the exclusion-principle correction does not include (*i*) the longitudinal momentum transfer arising from the virtual photon mass which, even at $\theta = 0°$, helps to separate the nucleons and mitigate the exclusion effect, and (*ii*) the contributions from the scalar virtual-photon component of the amplitude. To account for (*i*) we have used a procedure similar to that employed in optical-model calculations of ρ photoproduction.[19] This leads to the plausible result that the total three-momentum transfer must be inserted in Eq. (4). The scalar virtual-photon component enters the amplitude like the spin-flip component in photoproduction. Since the spin-nondependent term can arise only from photons polarized perpendicular to the production plane, we are not sensitive to it. Moreover, it vanishes when $\theta = 0°$.

These arguments and Eq. (4) lead to the prediction

$$R = 1 - \tfrac{1}{3}S(\vec{q}) - \tfrac{2}{3}(4\pi)^{-1}\langle r^{-2}\rangle_d \sigma_{\rm tot}(\pi^+ n). \qquad (5)$$

Equation (5) has been evaluated as in Ref. 14 and is shown in Fig. 2. The data are consistent with the calculation for larger momentum transfers but do not give evidence for a forward dip caused by the exclusion-principle term of Eq. (5).

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[1]Reaction (1) has been reported in C. N. Brown, C. R. Canizares, W. E. Cooper, A. M. Eisner, G. J. Feldman, C. A. Lichtenstein, L. Litt, W. Lockeretz, V. B. Montana, and F. M. Pipkin, Phys. Rev. Lett. 26, 987 (1971).

[2]This treatment of electroproduction is summarized in Ref. 1 and its references.

[3]P. Fleury, in *Methods in Subnuclear Physics*, edited by M. Nikolic (Gordon and Breach, New York, 1968), Vol. II, p. 541.

[4]C. N. Brown, C. R. Canizares, W. E. Cooper, A. M. Eisner, G. J. Feldman, C. A. Lichtenstein, L. Litt, W. Lockeretz, V. B. Montana, and F. M. Pipkin, Phys. Rev. Lett. 26, 991 (1971).

[5]C. Driver, K. Heinloth, K. Höhne, G. Hofmann, P. Karow, D. Schmidt, G. Specht, and J. Rathje, Phys. Lett. 35B, 77, 81 (1971).

[6]A. Baldin, Nuovo Cimento 8, 569 (1958).

[7]A. Ramanauskas, thesis, Cornell University, 1970 (unpublished).

[8]Photoproduction results have been summarized by B. Richter, in *Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September 1968*, edited by J. Prentki and J. Steinberger (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 1; K. Lübelsmeyer, in *International Symposium on Electron and Photon Interactions at High Energies, Liverpool, England, September, 1969*, edited by D. W. Braben and R. E. Rand (Daresbury Nuclear Physics Laboratory, Daresbury, Lancashire, England, 1970), p. 45; R. Diebold, in *Proceedings of the Boulder Conference on High Energy Physics, 1969*, edited by K. T. Mahanthappa, W. D. Walker, and W. E. Brittin (Colorado Associated University Press, Boulder, Colo. 1970), p. 3. Some more recent results can be found in A. Ito, R. Loe, E. C. Loh, A. Ramanauskas, D. Ritchie, and W. Schmidt, Phys. Rev. Lett. 24, 687 (1970).

[9]F. Berends, Phys. Rev. D 1, 2590 (1970).

[10]R. Manweiler and W. Schmidt, Phys. Rev. D 3, 2752 (1971).

[11]R. C. E. Devenish and D. H. Lyth, to be published.

[12]H. Fraas and D. Schildknecht, Phys. Lett. 35B, 72 (1971).

[13]V. Franco and R. J. Glauber, Phys. Rev. 142, 1195 (1966); R. J. Glauber and V. Franco, Phys. Rev. 156, 1685 (1967).

[14]A. Dar and A. Gal, Phys. Rev. Lett. 21, 444 (1968).

[15]K. Schilling, Nucl. Phys. B7, 498 (1968).

[16]A. Dar and A. Gal, Phys. Rev. D 1, 2714 (1970).

[17]D. I. Julius, Nucl. Phys. B27, 269 (1971).

[18]N. Jurisic, to be published.

[19]S. Drell and J. Trefil, Phys. Rev. Lett. 16, 552 (1966).