[7]G. L. Strobel, Nucl. Phys. A116, 465 (1968).
[8]K. L. Lim and I. E. McCarthy, Nucl. Phys. 88, 433 (1966).
[9]J. L. Snelgrove and E. Kashy, Phys. Rev. 187, 1246 (1969); W. T. H. van Oers and J. M. Cameron, Phys. Rev. 184, 1061 (1969).
[10]F. D. Becchetti, Jr., and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).
[11]K. E. Richie and B. T. Wright, Phys. Rev. 159, 839 (1967).
[12]R. M. Eisberg, D. Ingham, M. Makino, C. C. Kim, and C. N. Waddell, Nucl. Phys. A175, (1971).

Inclusive Proton Distributions in Electroproduction*

E. Lazarus,† D. Andrews,‡ K. Berkelman, G. Brown, D. G. Cassel, W. R. Francis, D. L. Hartill, J. L. Hartmann, R. M. Littauer, R. L. Loveless, R. C. Rohlfs, and D. H. White
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850

and

A. J. Sadoff
Physics Department, Ithaca College, Ithaca, New York 14850
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Measurements are reported for the process $e+p\rightarrow e+p+x^0$ at $Q^2=0.3$, 0.6, and 1.2 GeV^2 and for $0.875 \leq m_x^2 \leq 1.875$ GeV^2. Protons are produced predominantly backward in the center-of-mass frame, with average transverse momenta increasing with Q^2.

To supplement the recent data on deep-inelastic electron scattering[1] we have measured the distribution of recoil protons from the forward electroproduction of high-mass meson states. Electrons from the external beam of the Cornell synchrotron, inelastically scattered from protons at angles and energies corresponding to four-momentum transfer $Q^2=0.3$, 0.6, and 1.2 GeV^2 and final-state hadron effective mass $W=3.0$ GeV, were detected in a focussing magnetic spectrometer system.[2] In coincidence, protons emitted between about 45° and 80° laboratory angle were detected in a spark-chamber array behind a large-aperture bending magnet. Protons were identified by momentum and time of flight. Momenta above 230 MeV/c were detected. Data were corrected for detection efficiencies, geometric acceptance,[3] random coincidences, and target wall background. Radiative effects have been estimated[4] and are small, but no correction has been made to the data.

For each electron-proton event we compute the missing mass m_x in the reaction $e+p\rightarrow e+p+x^0$, and the four-momentum transfer t (the square of the difference between the initial and final proton four-momenta). In terms of the virtual-photon reaction, $\gamma(\text{virtual})+p\rightarrow p+x^0$, Q^2 is the spacelike photon mass squared, W (or $s^{1/2}$) is the total center-of-mass energy, m_x is the effective mass of the missing mesonic state, and t is the familiar momentum transfer variable.

The spectrum of missing masses below $m_x^2=0.8$ GeV^2 is dominated by the radiated photon peak at $m_x^2=0$, and by the ρ^0 and ω peak[5] at $m_x^2\approx 0.6$ GeV^2. The geometric aperture of the detection system imposes an upper limit near $m_x^2=2.0$ GeV^2. Figure 1 shows the Q^2, m_x^2, and t dependence of the virtual-photon differential cross section[6] $d\sigma/dm_x^2\,dt\,d\varphi$ in the range $0.875\leq m_x^2\leq 1.875$ GeV^2. The spectrum is flat in m_x^2 over the range displayed, with no evidence (even with finer m_x^2 bins) for production of φ, A_1, etc. The t distributions are rather gradual, fitting a form e^{Bt} with B essentially independent of m_x^2 and decreasing somewhat with Q^2: $B=2.6\pm0.2$, 2.2 ± 0.2, and 1.8 ± 0.2 GeV^{-2} at $Q^2=0.3$, 0.6, and 1.2 GeV^2, respectively (averaged over m_x^2). The Q^2 dependence is more striking when compared with the value $B\approx4.0$ GeV^{-2} obtained at the same W and m_x^2 in photoproduction.[7] It has been suggested[8] that a decrease in B with increasing Q^2 would be evidence for "shrinking" of the photon as it makes the transition from a vector-meson-dominant real photon to a pointlike deep inelastic photon.

To study the Q^2 dependence of the cross section, we integrate over φ (assuming no φ variation), integrate over t {from the kinematic limit $t_{\min}\approx-[(Q^2+m_x^2)/2\nu]^2$, assuming the best exponential fit}, and average over m_x^2 to get $d\sigma/dm_x^2$. We

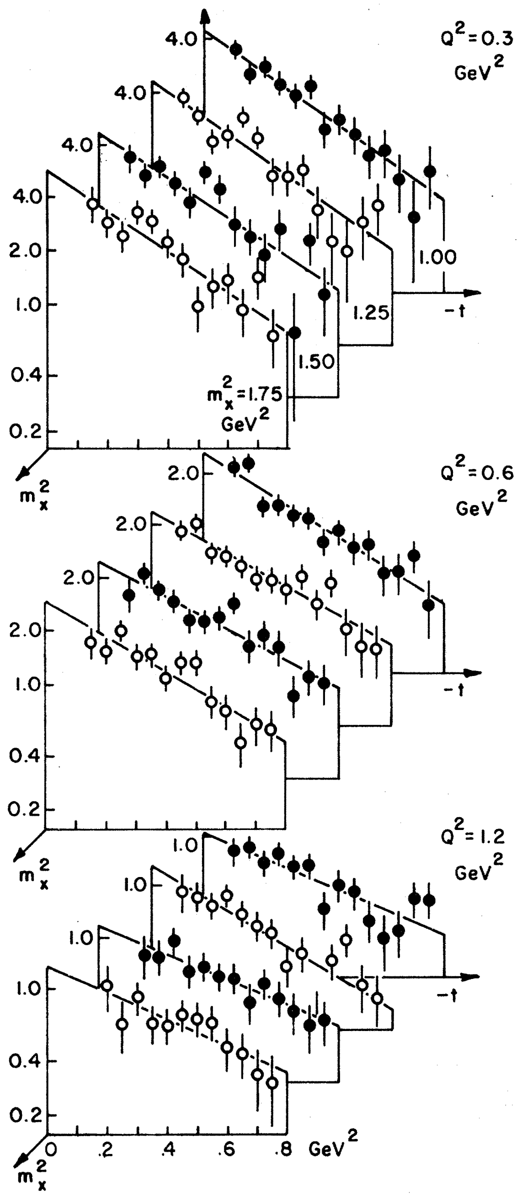

FIG. 1. Plots of $d\sigma/dm_x^2\, dt\, d\varphi$ for the reaction γ(virtual) + $p \rightarrow p$ + anything, as a function of m_x^2 and t for three values of Q^2. The units along the axes are the same for the three plots: m_x^2 and $-t$ in GeV^2, cross sections in μb/GeV^4 (logarithmic scale).

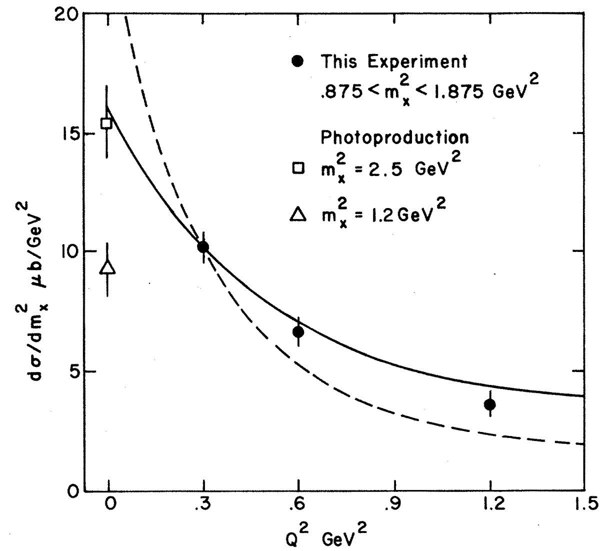

FIG. 2. The average $d\sigma/dm_x^2$ over the range $0.875 \leq m_x^2 \leq 1.875$ GeV^2, as a function of Q^2. The points at $Q^2=0$ are taken from photoproduction (Ref. 7). The curves are the total γ(virtual)$+p$ cross section (solid) and the function $(Q^2+m_\rho^2)^{-2}\exp(Bt_{\min})$ (dashed), both renormalized to pass through the measured $d\sigma/dm_x^2$ at $Q^2=0.3$ GeV^2.

plot the integral in Fig. 2 as a function of Q^2. For comparison we have included data at $Q^2=0$ from photoproduction[7] at the same W and two values of m_x^2. Since there is an apparent m_x^2 dependence in the photoproduction cross section that is not seen in the electroproduction data, it is difficult to make general statements about the Q^2 dependence. However, it seems clear that $d\sigma/dm_x^2$ is closer to the gradual Q^2 dependence of the total γ(virtual)$+p$ cross section[1] (solid curve) than to the prediction of naive ρ dominance (dashed curve).

The spectra in m_x^2 and t can be transformed into distributions in the proton momentum components in the center of mass, p_L (along the virtual photon direction) and p_T (transverse). The resulting invariant cross sections $2E\, d\sigma/dp_L \times dp_T^2\, d\varphi$ are flat in p_L and approximate the form $a\exp(-bp_T^2)$, with $a=72\pm4$, 41 ± 2, and 20 ± 2 μb/GeV^2 and $b=3.2\pm0.2$, 2.7 ± 0.2, and 2.4 ± 0.2 GeV^{-2} for $Q^2=0.3$, 0.6, and 1.2 GeV^2, respectively. At $Q^2=1.15$ GeV^2, $W=2.63$ GeV there are corresponding data for the forward hemisphere.[9] The $p_T=0$ cross sections are plotted against $x=p_L/p_{\max}$ and compared in Fig. 3. It is clear that protons are emitted predominantly in the backward hemisphere in the center of mass of the virtual-photon–proton collision, in contrast to some parton-model predictions.[10] If the invariant cross section is actually flat throughout the backward hemisphere, as it appears to be in Fig. 3, then the corresponding m_x^2 distribution at $t=t_{\min}$ is also flat out to the kinematic limit at $m_x^2=(W-M_p)^2$. If we assume that B is also constant, it is then possible to extend our measured values of $d\sigma/dm_x^2$ (Fig. 2) and arrive at a

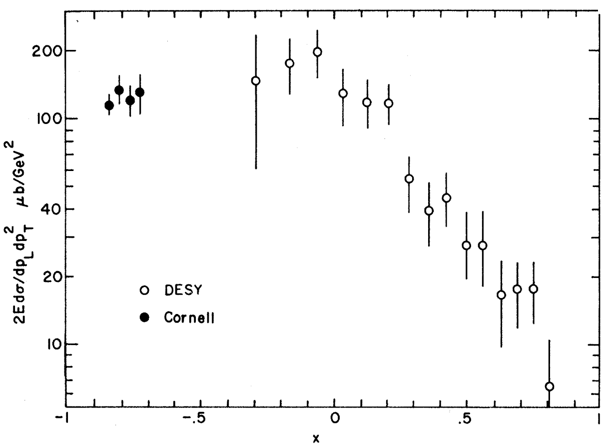

FIG. 3. The cross section $2E\, d\sigma/dp_L\, dp_T^2$ at $p_T=0$, $Q^2 = 1.2$ GeV^2, and $W=2.63$ (DESY) or 3.0 (Cornell), plotted against $x=p_L/p_{\max}$.

rough estimate of the total cross section for γ(virtual)$+p\to p+x_0$ for all $m_x^2>0.8$ GeV^2. The result is typically 40% of the total γ(virtual) $+p$ cross section. The remaining 60% is presumably accounted for[11] by meson states below $m_x^2=0.8$ GeV^2 and by neutron final states.

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†Present address: Brookhaven National Laboratory, Upton, N. Y. 11973.

‡Present address: Department of Physics, University of Rochester, Rochester, N. Y. 14627.

[1]G. Miller *et al.*, Phys. Rev. D 5, 528 (1972).

[2]The apparatus is described in somewhat more detail by E. Lazarus *et al.*, Phys. Rev. Lett. 29, 743 (1972).

[3]At each of the three Q^2 values two runs were taken with different positions of the proton spark chambers, in order to extend the range in m_x^2. The data from the two geometries were combined after taking account of the geometric acceptances.

[4]The soft-photon (real and virtual) correction has been estimated using a modified form of the prescription given by A. Bartl and P. Urban, Acta Phys. Austr. 24, 139 139 (1966). The contribution of hard-radiation events ($x^0=\pi^0+\gamma$) from the nucleon resonance region was estimated with a Monte Carlo technique using a reasonable model for resonance electroproduction. Soft radiation merely shifts the overall cross-section normalization slightly; the hard-radiation effect is completely negligible in our detection aperture.

[5]A plot of the complete mass spectrum from a preliminary analysis of this experiment is given by D. Andrews *et al.*, in *Proceedings of the Fifth International Symposium on Electron and Photon Interactions at High Energies, Ithaca, New York, 1971,* edited by N. B. Mistry (Cornell Univ. Press, Ithaca, New York, 1972), p. 273. The final results on the ρ^0 and ω contribution will be given in a separate report. Qualitatively, the conclusions of an earlier experiment [D. Andrews *et al.*, Phys. Rev. Lett. 26, 864 (1971)] are confirmed by the newer $\rho^0+\omega$ data.

[6]The usual virtual-photon flux factor Γ has been divided out of the measured electroproduction differential cross section. φ is the azimuthal angle of the state x^0 about the virtual-photon line.

[7]G. E. Gladding, J. J. Russell, M. J. Tannenbaum, J. M. Weiss, and G. B. Thomson (unpublished). We are indebted to M. J. Tannenbaum for useful discussions and information on their results before publication.

[8]H. Cheng and T. T. Wu, Phys. Rev. 183, 1324 (1969); R. W. Griffith, Phys. Rev. 188, 2112 (1969); J. D. Bjorken, J. B. Kogut, and D. E. Soper, Phys. Rev. D 3, 1382 (1971).

[9]F. W. Brasse, W. Fehrenbach, W. Flauger, K. H. Frank, J. Gayler, V. Korbel, J. May, P. D. Zimmerman, and E. Ganssauge, DESY Report No. 71/19 (unpublished).

[10]For example, see S. D. Drell, D. J. Levy, and T.-M. Yan, Phys. Rev. Lett. 22, 744 (1969), and 24, 855 (1970).

[11]The assumption has been made throughout this paper that there is no dependence of the cross sections on φ. The detection aperture in φ is not large enough to check this. In principle, since the virtual photon is polarized, it may be that the detected φ range is not representative of the average over φ.