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DEEP INELASTIC ELECTROPRODUCTION — THE PHOTON FRAGMENTATION REGION†

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ABSTRACT

Data are presented on the electroproduction of hadrons. The virtual photons are in the kinematic range $-.25 > q^2 > -3.00$ $(\mathrm{GeV}/c)^2$, $6 < W^2 < 30$ GeV^2. Hadrons produced with large laboratory momentum in the direction of the virtual photons are observed. The fraction of elastic ρ^0 mesons with longitudinal polarization is too large to support a vector dominance model for deep inelastic electron scattering. An excess of positive relative to negative hadrons is observed both with proton and with neutron targets. Other electroproduction experiments are reviewed. It is noted that as scaling turns on between $q^2 = 0$ and $q^2 = -1$ GeV^2 the electroproduced hadrons assume a less diffractive character consistent with the quark parton model.

INTRODUCTION

I will be describing data on the hadrons produced when electrons scatter from nucleons with high energy losses and large four-momentum transfers. As with the other experiments reported today this experiment was motivated by the unexpected "scaling" behavior of the cross section for deep inelastic electron scattering.[1] The hope is that if the scaling behavior is due to single photon transfer from the electron to a pointlike "parton" within the nucleon, then the properties of the partons might somehow be manifested in the properties of the hadrons which emanate from the collision. The properties of these hadrons should be qualitatively different than in photoproduction, where the coupling of the photon to the known vector mesons appears to dominate the physics.[2]

With this object in mind, let me now discuss the kinematic region of the data which I will present. There are two sets of variables — those pertaining to the exchanged photon (γ^*), and those pertaining to the observed hadrons. The exchanged photons here have invariant mass squared in the range $-.25 > q^2 > -3.0$ GeV^2. They produce center-of-mass energy squared in the γ^*p or γ^*n collision in the range $6 < W^2 < 30$ GeV^2. The large average W^2 of ~ 18 GeV^2 has the effect of reducing the well understood two-body processes to being a small fraction of the cross section. The cross section for $\gamma^*p \to \pi^+ n$, for instance, falls as W^{-4} while the total γ^*p cross section remains nearly constant.[3]

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Turning to the hadrons, this experiment sees those which are in the forward hemisphere in the photon-nucleon c.m. system. These hadrons carry away most of the virtual photon momentum in the lab, and are said to be in the "photon fragmentation region". In the vector dominance model, one would expect to see ρ's in this region with a forward cross section intimately related to the total γ^*p cross section.[4] In the quark-parton model, one would expect the "struck parton" to appear in this region, dressed more often as a π^+ than as a π^-.[5] This is the effect of the valence quarks. With either a proton or a neutron target one expects the γ^* to be absorbed by a $+2/3$ charged quark more often than by a $-1/3$ charged quark. The former can become a π^+, the latter a π^-. The π^+/π^- ratio should be greater than 1 for either a proton or a neutron target, but the effect should be larger in the proton case.

EXPERIMENTAL PROCEDURE

The experiment was performed at the Stanford Linear Accelerator Center by Gary Feldman, Bill Lakin, Fred Martin, Martin Perl, Eric Petraske, Bill Toner and me.[6] The apparatus is shown in Fig. 1. The incident beam contained 19.5 GeV electrons. The target was 4 cm long and filled sometimes with H_2 and sometimes with D_2. Particles leaving the target in the angular region $30 < \theta < 300$ milliradians entered a large aperture magnetic spectrometer. At the downstream end of this was an array of lead-lucite shower counters. Whenever an electron with energy greater than 5 GeV was detected by this array, the optical spark chambers were pulsed and photographed to detect hadrons. The forward, low-energy, electromagnetic backgrounds from the target did not enter the spark chambers. They passed through the magnet undeflected in the field-free region created by a superconducting beam pipe. The experiment had no means for distinguishing between pions, kaons, and protons.

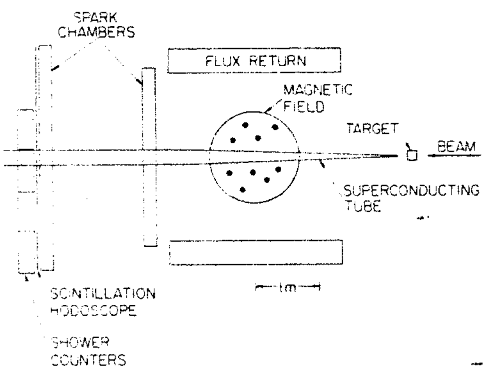

Fig. 1. Schematic view of the apparatus.

The pictures were scanned and measured with a combination of 2 systems — an automatic flying-spot digitizer, and a manual film-plane digitizer. After the events were reconstructed, they were summed and reduced to cross sections through the use of standard Monte Carlo and maximum-likelihood techniques. The cross sections are normalized to the number of detected electrons, which is the total number of virtual photon interactions in the data set.

RESULTS

To test the vector dominance model we studied the reaction

$$\gamma^* p \rightarrow \rho^0 p, \quad \rho^0 \rightarrow \pi^+\pi^- \quad . \tag{1}$$

In each event we detected a scattered electron, which told us the 4-momentum of the γ^*, and a $\pi^+\pi^-$ pair. By calculating the missing mass we were able to determine whether the only undetected particle was a proton. We found 238 events satisfying all "rho" criteria. The observed rho cross section is shown in Fig. 2. While this channel represents 11% of the total cross section for real photons,[2] it becomes a rapidly smaller fraction as the photon becomes more virtual. The falloff is consistent with the falloff of the rho propagator with q^2.

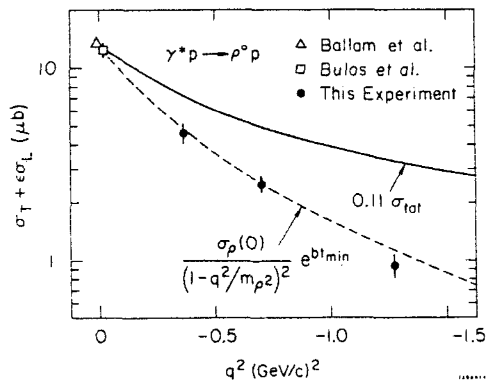

Fig. 2. The total cross section for reaction (1).

Because this experiment detects the ρ via its decay products, it is able to determine the ρ polarization. We measured R, the production ratio of longitudinal to transverse rhos (Fig. 3). This is 0 in photoproduction because there are no longitudinal photons. If we assume that R increases as

$$R = -\xi^2 \frac{q^2}{m_\rho^2} \qquad (2)$$

then we determine ξ^2 to be $0.45^{+0.15}_{-0.10}$. This fit is shown in Fig. 3. Within the vector dominance model, this turn on of the longitudinal rhos is too fast to accommodate the low total cross section for longitudinal photons.[4] Also shown in Fig. 3 is the R data from other experiments.

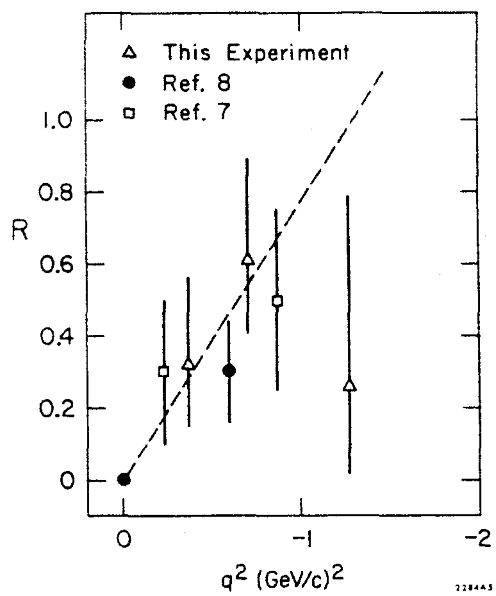

Fig. 3. The ratio of longitudinal to transverse ρ^0 production.

To explore the more general properties of the hadrons produced in deep inelastic electron scatters, we studied the inclusive reactions

$$\gamma^* p \to h^\pm + \text{anything}\,, \qquad (3a)$$

$$\gamma^* n \to h^\pm + \text{anything}\,. \qquad (3b)$$

The cross sections were parametrized with the now standard variables relative to the γ^* direction in the γ^*p or γ^*n system:

ϕ - the azimuthal angle ,

$p_\perp^2$ - the transverse momentum squared, and

x - the longitudinal momentum relative to its largest possible value .

Because we have no way of distinguishing various types of hadrons from one another, we assume that all are π's for calculating x, but call them h's.

The ϕ distributions are consistent with being uniform — this is the prediction of the parton model.[9] We cannot, however, rule out $\cos\phi$ or $\cos 2\phi$ terms as large as 30% for some regions of q^2, W^2 and x. An 8% $\cos 2\phi$ term is observed for reaction (3a) with real photons.[10]

Fits to the $p_\perp^2$ slopes for $0 < p_\perp^2 < 0.7$ GeV^2/c^2 are shown as a function of q^2 in Fig. 4. Here one sees no striking difference between inclusives from the H_2 target and those from D_2 target. This suggests that the coherent effect in deuterium is small. As shown, the slopes are generally broader (b smaller) than those observed at $q^2 = 0$,[10] for the same $p_\perp^2$ range and for $W^2 = 18.3$ GeV^2.

The x dependence of the Lorentz-invariant cross section is shown in Fig. 5. Also shown is the x distribution for the inclusive production of π^- at $q^2 = 0$.[10] In both cases the π's from photoproduction and from electroproduction have similar shapes and normalizations.

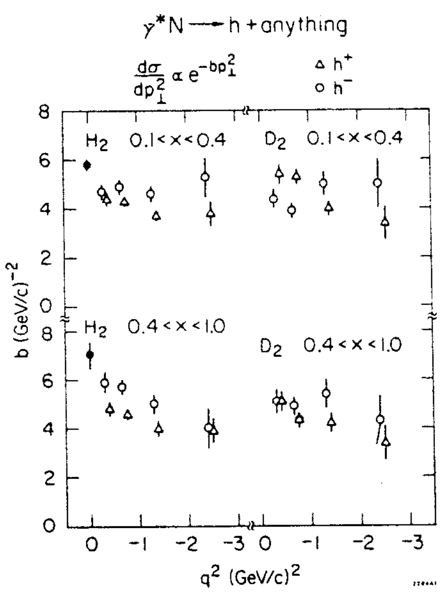

Fig. 4. The transverse momentum slopes for inclusive hadron production.

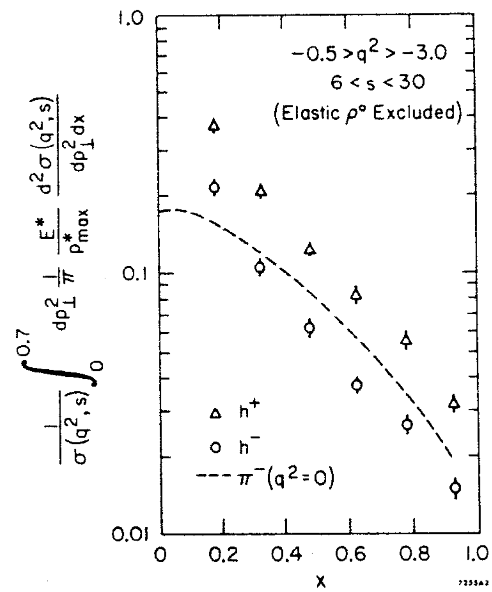

Fig. 5. The Lorentz-invariant cross section for inclusive hadron production.

Most remarkable in Fig. 5 is the fact that there are about twice as many h^+ as h^- over the entire x range. This is the sort of behavior which one expects from the quark-parton model, but not from vector dominance. This effect is shown more explicitly in Fig. 6 where the "charge ratio" is plotted as a function of x for 4 different values of the scaling parameter $\omega = -2\,M\nu/q^2$. (Here M is the proton mass, and ν the photon laboratory energy.) Looking first at the proton column we see that the charge ratio is consistent with being x independent for $x > .1$. The ratio is generally larger for low ω (high q^2). It is displayed here as a function of ω purely for variety; we are unable to distinguish between a q^2-dependent charge ratio, and an ω-dependent charge ratio with our data.

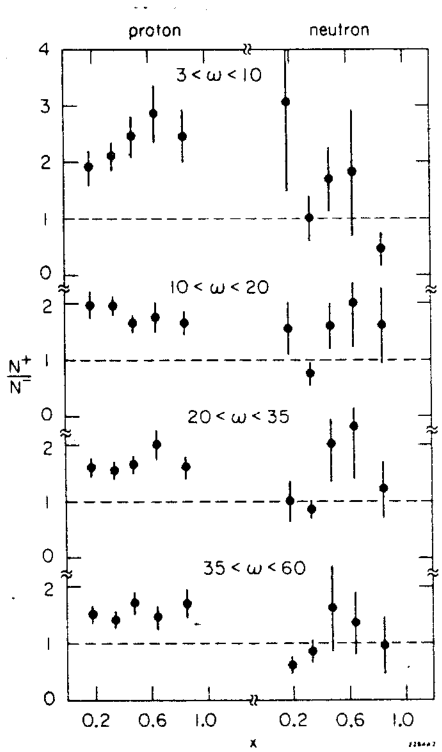

Fig. 6. The charge ratio for both proton and "neutron" targets.

We have also extracted the charge ratio from the "neutron" target. This was done assuming that the cross section from the deuteron is the simple sum of cross sections from the proton and from the neutron. The results are shown in Fig. 6. The errors shown are statistical only. There may be additional systematic errors no larger than 20%. The data are admittedly crude — from them we can conclude only that the average effect is smaller from the neutron target than from the proton target, but greater than or equal to 1. This is what one expects in the quark-parton model.

In the future we plan to improve these measurements by taking 100x more data, with the optical chambers replaced by multi-wire proportional chambers, and with a Čerenkov counter for hadron identification. This is being done in cooperation with Craig Bolon, Dick Lanza, Dave Luckey, Jim Martin and Lou Osborne from MIT.

REVIEW OF OTHER WORK

I will now turn to a more general discussion of the present experimental situation. Figure 7 shows the regions of the q^2 - W^2 plane in which experimenters have studied the deep inelastic electroproduction of hadrons. I have limited the scope to include only inclusive experiments, and experiments to study the rho. I have also arbitrarily eliminated the resonance region $W^2 < 4$ GeV^2. As a tribute to all of these experimenters I should point out that a very coherent picture is emerging, with far more agreement than disagreement over the behavior of the hadrons.

Consider the kinematic region of these experiments. This can be characterized as $\omega > 4$ and $q^2 < 0$. We know from the present single-arm electron and muon scattering data[1] that 3 basic statements can be made about this region. First the γ^*p and γ^*n total cross sections are nearly equal; the difference

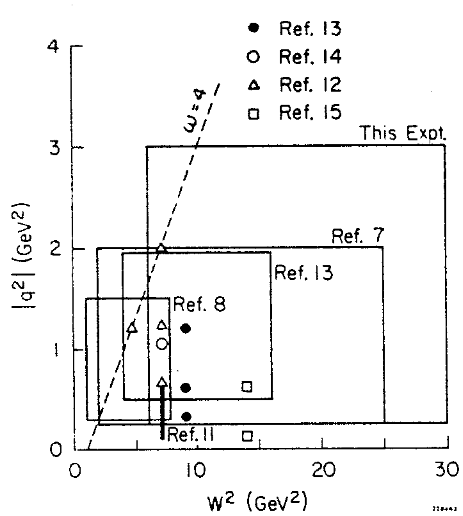

Fig. 7. The kinematic regions of various electroproduction experiments.

varies from 25% at $\omega = 4$ to less than 5% at $\omega = \infty$ ($q^2 = 0$).[17] Second, the inelastic structure function νW_2 appears to be flat, depending little on anything, for $q^2 < -.5$ GeV^2 and $\omega > 4$. Lastly, νW_2 depends mostly on q^2, not on ω, for $q^2 > -1$ GeV^2. The implications of this total cross section behavior for the present experiments studying hadrons might be the following: They might see scaling turn on as a function of q^2 for $0 > q^2 > -1$ GeV^2, but not see anything terribly dramatic thereafter. The really interesting behavior may begin only where νW_2 becomes interesting — at $\omega < 4$. Electroproduction experiments are being planned for this region, but we will have to wait a year or two to learn the results.

Now, let us turn to several conclusions which can be drawn about the behavior of electroproduced hadrons in the kinematic region of Fig. 7. Except for this experiment, all data reported is from proton targets.

First, consider elastic ρ production, reaction (1). In the vector dominance model this plays the roll of the elastic channel. Our understanding of the total cross section for reaction (1) is largely the same as at the time of the Cornell conference,[18] only now there is more data over a larger q^2 range and the agreement is better. This cross section falls more rapidly than the total $\gamma^* p$ cross section, and at an absolute rate which is consistent with the ρ propagator. This behavior is shown for our experiment by the dashed line in Fig. 2: a similar behavior is seen in all other experiments.[7,8,11,13,15]

The new information on the elastic ρ channel comes from experiments which measure the ρ polarizations over the entire polarization range by detecting the π^+ and the π^-. This information comes from 3 experiments which presented preliminary information at Batavia,[6,7,8] and from which the picture has since crystalized. Essentially, the longitudinal turn-on parameter, ξ^2, defined in equation (2) is somewhere in the range $.4 \pm .1$, and is not consistent with the value .06 required by the vector dominance model.[4]

Second, consider the inclusive π^+ and π^- cross sections. These have been observed over the entire x range by 2 experiments,[7,8] and over portions of the x range by several others.[6,11,12,13,14] Each experiment sees basically the same x shape as is observed in photoproduction at the same W^2, and with the proper normalization. The principal deviation is the absence of the π's in the ρ decay region, $x \approx .7$. This effect is most dramatically seen in the data from the Harvard-Cornell experiment.[12]

It is of interest that the π^+ x distribution appears to "scale", i.e., be independent of q^2 for fixed ω. This is demonstrated explicitly by the Harvard-Cornell experiment,[12] and less directly by the fact that all experiments see about the same x distribution over the entire explored region of Fig. 7.

Let me mention briefly the data on transverse momentum distributions, and slope parameters. Here the situation is unclear. For a given reaction it is difficult to compare slopes of different electroproduction experiments, or of a given experiment and a photoproduction experiment. This is because slopes tend to depend on x, on W^2, and on the $p_\perp^2$ range. With these difficulties in mind, I know of no experiment which reports a significant q^2-dependence of a π slope.

The biggest surprise in the inclusive electroproduction of π's is the growing π^+/π^- charge ratio in the photon fragmentation region. This is shown for $0.4 \lesssim x \lesssim 0.8$ in Fig. 8. All experiments shown, except ours, had π-k-p separation. The upper cut of 0.8 is chosen to eliminate π's from the known 2-body and quasi 2-body channels. The ratio clearly grows from ~1.3 at $q^2=0$ to ≥ 2.0 for $q^2 < -1$ GeV^2. When one compares the low W^2 and high W^2 points in Fig. 8 one is tempted to conclude that the charge ratio is a q^2-dependent rather than an ω dependent effect in this q^2 range. In either case, the charge asymmetry indicates that diffractive effects are less important in deep-inelastic electroproduction. than in photoproduction. We now have evidence that the forward charge ratio is greater than 1.0 from the neutron target as well.

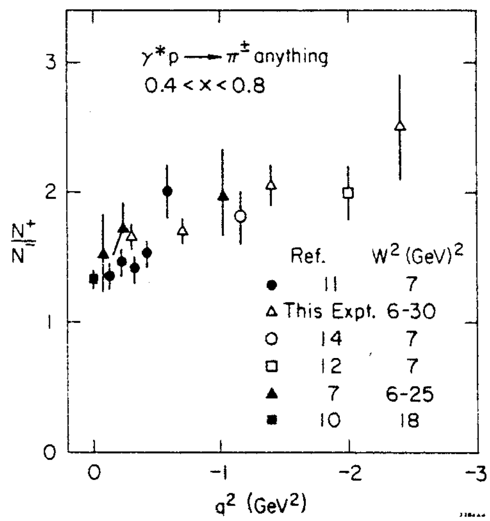

Fig. 8. The charge ratio extracted from various electroproduction experiments.

Third, we will turn to the protons. From various sources we have learned that they are more complicated than the π's. From the Harvard-Cornell experiment[12] we have learned that forward inclusive protons don't scale. They go away with increasing W^2, and at a given W^2 are independent of q^2. From the SLAC hybrid bubble chamber[7] we have learned that the diffractive peak of protons near x = -1 in photoproduction goes away with increasing $|q^2|$. There is evidence that the transverse momentum distribution for backward protons broadens with $|q^2|$, both for the elastic ρ channel,[6, 7, 8, 13, 15] and for inclusive protons.[7, 13]

Fourth, there is considerable evidence that there are no coherent effects in nuclei below $q^2 \approx -0.5$ GeV^2. This was shown today by the $A^{1.00}$ dependence of the total γ^* nucleus cross section observed in the Brookhaven μ-scattering experiment[16] and in electron scattering.[1] The absence of coherent effects is also seen in the similarity of the inclusive pion slopes from H_2 and D_2 in this experiment.

CONCLUSIONS

I will conclude with some speculation. Most of the effects that we have seen have been q^2-dependent, and they have occurred in the region between $q^2=0$ and $q^2=-1$ GeV^2. These include the going away of the elastic ρ, the growing forward charge ratio, the disappearing backward protons, the disappearing coherent effects, and the less steep slopes of backward protons. Each of these effects is anti-diffractive in character. It could well be that these are all due to the going away of the known vector mesons — $\rho, \omega, \phi, \rho'$.

In this model, the process which is left when the vector mesons have gone is the process which produces scaling. There is some evidence that this mysterious process is even present in photoproduction. It is the 20-40% of the γp total cross section which cannot be explained by the known vector meson couplings.[19] It is the non-diffractive component of photoproduction which produces a π^+/π^- ratio of ≈ 2 at $x = .8$ and high $p_\perp$.[20]

So far we have gained little insight as to what this process actually is, and whether it really involves partons. While the deep inelastic electroproduction data presented here is certainly all consistent with partons, it presents no really compelling evidence for or against. For this we must await the results of more extensive single-arm electron scattering measurements, and the results of electroproduction experiments with both proton and neutron targets over a larger ω range.

It is still possible that photons coupled to higher mass vector mesons dominate the physics for $q^2 < -1$ GeV^2 and provide our mystery process. For this to be true either equation (2) must break down in this q^2 range, or ξ^2 must be smaller for the higher mass mesons. Furthermore, there must be a significant non-diffractive component to the vector meson-nucleon interaction.[21] This gives a vector dominance model which is less attractive than earlier, simpler vector dominance models.

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