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ON THE IMPORTANCE OF PION ELECTROPRODUCTION AT HIGH ENERGY

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A B S T R A C T

High energy pion electroproduction is analyzed and shown to be very useful as a source of the pion electromagnetic form factor and as a means of testing the vector dominance model and finite energy sum rule predictions for electromagnetic processes.

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We wish in this letter to point out that pion electroproduction measurements at high energy would provide a wealth of desirable information. In particular one could obtain: 1) the pion electromagnetic form factor; 2) a test of models which predict the size of the 0^0 pion photoproduction cross-section (such as the electric Pom model); 3) a clean and rather complete test of the vector dominance model for pion production and 4) tests of some recent theoretical speculations.

What we are suggesting is that the process $e^- + p \rightarrow e^- + \pi^+ + n$ be measured as a function of virtual (spacelike) photon mass q^2 , at large energies s (say $s \geq 5 \text{ GeV}^2$) over a range of invariant momentum transfers t , including the near-forward region $|t| < 2m^2$. The figure defines our notation and relevant kinematical quantities. The cross-section for this process may be written (one photon exchange approximation) as

$$\frac{d^4\sigma}{d\Omega_e dE_2 dt d\phi} = \Gamma_T \left\{ \frac{(1+\epsilon \cos\phi)}{2} \frac{d\sigma^{\parallel}}{dt} + \frac{(1-\epsilon \cos\phi)}{2} \frac{d\sigma^{\perp}}{dt} + \epsilon \frac{d\sigma^S}{dt} - 2\sqrt{\epsilon(\epsilon+1)} \cos\phi \frac{d\sigma^I}{dt} \right\} \quad (1)$$

where

$$\Gamma_T = \frac{\alpha}{4\pi^2} \frac{1}{(-q^2)} \left(\frac{E_2}{E_1} \right) \left(\frac{s-m^2}{2m} \right) \frac{2}{1-\epsilon} \quad (2)$$

may be interpreted as a flux of virtual transverse photons, and

$$\epsilon = \left(1 + 2(1 - v^2/q^2) \tan^2 \theta/2 \right)^{-1} \quad (3)$$

as their polarization. The quantities $d\sigma^{\parallel}$ and $d\sigma^{\perp}$ are cross-sections for pion production by virtual photons plane polarized parallel to and perpendicular to the production plane respectively; $d\sigma^S$ is the contribution of scalar photons and $d\sigma^I$ a scalar transverse inter-

ference term ^{*}). Finally, Ω_e and E_2 are the laboratory solid angle and energy respectively of the scattered electron, t the invariant momentum transfer to the target proton, and ϕ the angle seen in the laboratory between the plane formed by the electron momenta and the momenta of the $\pi^+ n$ system ^{**}). At $q^2=0$ $d\sigma^{\parallel}$ and $d\sigma^{\perp}$ are the quantities measured in photoproduction and $d\sigma^S$ and $d\sigma^I$ vanish according to $d\sigma^S \sim q^2$, $d\sigma^I \sim \sqrt{-q^2}$.

Let us first recall the situation in charged pion photoproduction ($q^2=0$) ^{***}). At high energy $s^2 \frac{d\sigma}{dt}$ shows a sharp, energy independent peak inside $-t=m_\pi^2$. Since the one-pion exchange contribution (OPE) is known to vanish at $t=0$ the forward cross-section must arise entirely from other contributions to the amplitude, such as s channel poles, absorption, Regge cuts, etc. All the latter, not having the pion pole, reasonably may be expected to be slowly varying in t over an interval $\Delta t \sim 2m_\pi^2$. The steep fall of $\frac{d\sigma}{dt}$ away from $t=0$ comes about from destructive interference between the rapidly growing OPE amplitude and the "other" contributions. A check of the belief that amplitudes without OPE are slowly varying for $\Delta t \sim 2m_\pi^2$ is provided by the observed constancy of $\frac{d\sigma^{\perp}}{dt}$.

Now consider the cross-section $\frac{d\sigma^{\parallel}}{dt}$ defined above for virtual photons ($q^2 \neq 0$). Again one has a OPE term, now proportional to the pion electromagnetic $F_\pi(q^2)$, as well as the other contributions to the amplitude. For convenience let us work with an energy independent amplitude ^{****})

^{*}) The division of (1) into a flux times a virtual particle cross-section is of course an artificial one and not unique. We have followed the normalization convention of Hand, Ref. 1).

^{**}) If one averages over ϕ , one measures only the transverse, $d\sigma^T = \frac{1}{2}(d\sigma^{\parallel} + d\sigma^{\perp})$, and scalar, $d\sigma^S$, cross-sections as in the familiar inelastic electron-proton scattering experiments.

^{***}) For a review of the data, see Ref. 2), and for a theoretical discussion, see Ref. 3).

^{****}) Of course, one can and should check experimentally that the same energy behaviour is observed in electroproduction as is seen in photoproduction. Our remarks will not be changed if a different energy behaviour is observed.

$$A(t, q^2) = A_0(t, q^2) + A_{\text{OPE}}(t, q^2) \quad (4)$$

where

$$s^2 \frac{d\sigma''}{dt} \propto |A(t, q^2)|^2$$

For $|t| \lesssim 2m_\pi^2$ Eq. (4) may be well approximated by

$$A(t, q^2) \cong A_0(0, q^2) + F_\pi(q^2) t (t - m_\pi^2)^{-1} \quad (5)$$

Thus, one can establish the q^2 dependence of the other contributions A_0 by looking at $t=0$ and the q^2 dependence of F_π by looking at the region $-t \approx m_\pi^2$. The assumed constancy in t of A_0 will be credible if $d\sigma^\perp(s, t, q^2)$ is verified to be constant in t over this interval. Recall that $d\sigma^\perp(s, 0, q^2) = d\sigma''(s, 0, q^2)$ since the π^+n system ceases to define a plane at $t=0$ (the conspiracy condition). One may also obtain $F_\pi(q^2)$ from the OPE contribution ^{*}) to $d\sigma^S$ as has been attempted at low energies in the region of the $\Delta(1238)$ ⁴⁾.

It is clear, too, that electroproduction allows a nice test of models which predict the height of the forward peak in photoproduction. For example the electric Born model would have $A_0(0, q^2) \sim F_1(q^2)$ where F_1 is the Dirac form factor of the proton ^{**)}. More realistically one could test, over a range of q^2 , the construction of the forward ^{3), 5)} (and non-forward) amplitude by resonance saturation of the finite energy sum rules once the required transition form factors are measured. This ought to be very interesting.

^{*}) As $t \rightarrow 0$ one has for the $(\text{OPE})^2$ contributions $d\sigma^S \sim -t$, $d\sigma^I \sim (-t)^{\frac{3}{2}}$.

^{**)} For arbitrary q^2 the anomalous magnetic moment does not contribute at $t=0$ to leading order in s .

The vector meson dominance model (VMD) predicts the size and q^2 dependence of the entire electroproduction amplitude. Here we are interested in both forward and non-forward t values. All parts of the amplitude are supposed to have a dependence $\sim(m_\rho^2 - q^2)^{-1}$ plus similar contributions from the ω and ϕ mesons.

Attention, so far ^{2),6)}, has concentrated on the VMD predictions for pion photoproduction using data from $\pi^- p \rightarrow \rho^0 n$. The prediction for $d\sigma^\perp + d\sigma^\parallel$ seems to be satisfactory but that for the asymmetry $a = (d\sigma^\perp - d\sigma^\parallel)/(d\sigma^\perp + d\sigma^\parallel)$ seems to be very bad ²⁾. The prediction for a depends critically on the rho meson helicity density matrix element ρ_{1-1} which remains subject to experimental ambiguity ⁶⁾.

By using the electroproduction data one could eliminate entirely the need for the vector meson data by examining the generalized "radius" predictions ^{*)} of the VDM

$$\left. \frac{d^2 \sigma^{\perp, \parallel}(s, t, q^2)}{dq^2 dt} \right|_{q^2=0} = \frac{2}{m_\rho^2} \cdot \frac{d\sigma^{\perp, \parallel}(s, t, 0)}{dt}. \quad (6)$$

It should be noted that the VDM is expected to work even better for the slope $\frac{d^2 \sigma}{dq^2 dt}$ than for $\frac{d\sigma}{dt}$ since the q^2 dispersion relation for the former emphasizes even more the low mass part of the spectral function ^{**)} . Also note the happy fact that because of the near equality $m_\omega \approx m_\rho$ it is not necessary to form the charge average

*) These predictions as well as those of Eqs. (7) and (8) follow from the application of the VDM to kinematic singularity free invariant amplitudes. Only the leading terms as $s \rightarrow \infty$ have been kept. To this order they coincide with the use of s channel helicity amplitudes. See Ref. 7).

**) The first and most clear-cut failure of the VDM was its failure to predict properly the isovector radius of the nucleon form factors. The authors of Ref. 8) suggest that there may be enough contribution to the spectral function from the $\pi\pi$ continuum below the rho resonance region to influence slope predictions. This heightens our interests in the slope predictions here. For a discussion of the slopes in inelastic electron-proton scattering, see Refs. 9) and 10).

$$\frac{1}{2} \{ d\sigma(\gamma p \rightarrow \pi^+ n) + d\sigma(\gamma n \rightarrow \pi^- p) \}$$

to eliminate the troublesome $\rho - \omega$ interference terms in Eq. (6).
(It should be safe to continue to neglect the ϕ contribution.)

A further important test of the VDM is afforded by its predictions ⁷⁾ for the scalar and interference terms in Eq. (1), namely

$$\frac{1}{-q^2} \frac{d\sigma^S(s, t, q^2)}{dt} = \left(\frac{e}{2\gamma_p} \right)^2 \left(\frac{m_\rho^2}{m_\rho^2 - q^2} \right)^2 \left\{ \frac{1}{m_\rho^2} \rho_{00} \frac{d\sigma(\pi^- p \rightarrow \rho^0 n)}{dt} \right\} \quad (7)$$

and

$$\frac{1}{\sqrt{-q^2}} \frac{d\sigma^I(s, t, q^2)}{dt} = \left(\frac{e}{2\gamma_p} \right)^2 \left(\frac{m_\rho^2}{m_\rho^2 - q^2} \right)^2 \left\{ \frac{1}{m_\rho} (Re \rho_{10}) \frac{d\sigma(\pi^- p \rightarrow \rho^0 n)}{dt} \right\}$$

$$\gamma_p^2 / 4\pi \approx 0.5. \quad (8)$$

The left-hand sides of Eqs. (7) and (8) should be taken as the average of π^- and π^+ electroproduction. The predictions (7) and (8) are of no less importance than those for $d\sigma^{||, \perp}(s, t, q^2)$ ^{*)}.

Finally, consider some other recent speculations. Avni and Harari ¹²⁾ have suggested that the mechanism for producing the near forward structure observed in photoproduction is very mass dependent and that such structure may not be observed in $\pi^- p \rightarrow \rho^0 n$. (Necessarily a breakdown of the VDM.) In electroproduction we can test this conjecture in the region of spacelike masses. [If the authors of Ref. 12)

*) Iso and Schildknecht, Ref. 11), also emphasize the importance of testing VDM predictions in electroproduction. They, however, are especially concerned with the controversial use of the Donohue-Högaasen spin axes. We feel this is wrong. The helicity axes should be used for the density matrices in Eqs. (7) and (8). See Potter and Sullivan, Ref. 7).

are correct, our programme for obtaining $F_{\pi}(q^2)$ from $d\sigma''(s,t,q^2)$ will be more difficult since the OPE contribution will be less easily identified.] Cho and Sakurai¹³⁾ have gone to the opposite extreme and proposed an extension of the VDM which predicts the scalar photon amplitude in terms of the transverse ones. This, too, can be put to the test in electroproduction.

We summarize. Electroproduction measurements at large s over a range of q^2 and t are highly desirable. They would provide: significant tests of some present models of high energy photoproduction, the pion form factor, new tests of the VDM, and tests of related theoretical suggestions. Let us record also our conviction that even if all our above remarks turn out to be wrong, pion electroproduction is still of great interest. It is the most accessible two-body process which can be probed as a function of an external mass variable. In this same spirit it would be interesting to know its behaviour in the "deep inelastic" region to see how this one channel fits onto the scaling observed in the total inelastic electron-proton scattering measurements. Electroproduction of π^- and π^0 is no less interesting.

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$$\begin{aligned}
 t &= (p_p - p_n)^2 & q^2 &= (k_1 - k_2)^2 \\
 s &= (p_\pi + p_n)^2 & m\nu &= p_p \cdot q
 \end{aligned}$$

Definition of kinematical quantities used to describe pion electroproduction $e^- + p \rightarrow e^- + \pi^+ + n$. The electron variables E_1 , E_2 , θ all refer to laboratory quantities.