Regge description of charged pseudoscalar meson electroproduction above the resonance region

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(Received 10 July 1997)

A gauge invariant model based on π and ρ Regge trajectory exchanges provides a successful and economical description of the forward charged pion electroproduction reactions above the resonance region. Its sensitivity to the meson form factors is investigated in kinematics where the pion electromagnetic form factor will be extracted at high Q^2 at TJNAF. An extension to K^+ electroproduction is presented.
[S0556-2813(98)04603-2]

PACS number(s): 13.60.Le, 12.40.Nn, 13.40.Gp

A fundamental quantity of hadron structure is the pseudoscalar meson ($\pi,K,\ldots$) electromagnetic form factors and their evolution as a function of the four-momentum transfer squared $-Q^2$. At low Q^2, a theoretical interpretation in terms of QCD is difficult as one is in the nonperturbative regime of QCD. In this regime, data permit one to test different QCD inspired models. At large values of Q^2, one enters the domain of perturbative QCD (PQCD) where the form factors show a scaling behavior [1] and where an interpretation in terms of quark and gluon degrees of freedom becomes possible. The new generation of high energy, high duty factor electron facilities such as TJNAF makes it possible to explore the meson form factors at higher Q^2 with unprecedented accuracy [2] and to determine the scale at which one goes over to the domain of PQCD. However, a good knowledge of the charged pseudoscalar meson electroproduction reaction mechanism at high energy and low momentum transfer is indispensable, since no free meson targets are available. In this paper, we show that a Regge trajectory exchange model is definitely superior to the Born diagram model [3,4], when compared with the available data and should therefore be used for extracting pseudoscalar meson form factors.

In Refs. [5,6], a gauge invariant Regge trajectory exchange model was shown to be able, at high energy (i.e., above the resonance region) and at low momentum transfer ($t<2$ GeV^2), to give an economical description of the unpolarized and polarized data for the charged pion photoproduction reactions as well as for the $K^+\Lambda$ and $K^+\Sigma^0$ photoproduction data. The model is simple, as it is based on the π and ρ (respectively, K and K^*) Regge exchanges in the t channel. Since a simple t-channel π-pole exchange is not gauge invariant, it was made explicitely gauge invariant by the proper reggeization of the s-channel nucleon pole diagram (for the π^+ production) as explained in detail in Refs. [5,6]. The model is parameter free as the coupling constants at the vertices are well determined by precise studies and analyses in the resonance region. Its extension to the case of electroproduction is straightforward. As the π- and ρ-exchange amplitudes are separately gauge invariant, two different electromagnetic form factors are introduced for the π and ρ exchanges without violating the gauge invariance of the theory. We use monopole form factors

$$F_{\pi,\rho}(Q^2)=[1+Q^2/\Lambda^2_{\pi,\rho}]^{-1}, \tag{1}$$

with $Q^2=-q^2$, where q is the spacelike virtual photon four-momentum. The analysis in Ref. [7] yielded $\Lambda^2_\pi = 0.462$ GeV^2. The ρ mass scale is unknown and we use $\Lambda^2_\rho=\Lambda^2_\pi$ as a first guess.

In Fig. 1 we plot the π^+ electroproduction cross section for $Q^2 = 1.2$ GeV^2 at two energies for which data from Cornell [8] exist and we compare a Regge model and a Born model. The same vertices and coupling constants are used in both models and the Born model is obtained by replacing the

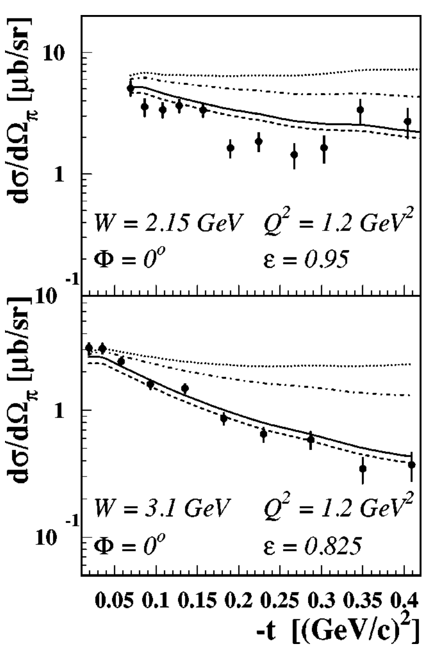

FIG. 1. Comparison of the $\gamma^*+p\to\pi^++n$ differential electroproduction cross section at two energies W = 3.1 GeV and W = 2.15 GeV at Q^2 = 1.2 GeV^2 and for Φ = 0° (in plane). Dash-dotted lines, π Born exchange with Λ^2_π = 0.462 GeV^2; dotted lines, $\pi+\rho$ Born exchanges with $\Lambda^2_\pi=\Lambda^2_\rho$ = 0.462 GeV^2; dashed lines, $\pi+\rho$ Regge exchange model with $\Lambda^2_\pi=\Lambda^2_\rho$ = 0.462 GeV^2; solid lines, $\pi+\rho$ Regge exchange model with $\Lambda^2_\pi=\Lambda^2_\rho$ = 0.50 GeV^2 which gives a better fit to the data. The data are from Ref. [8].

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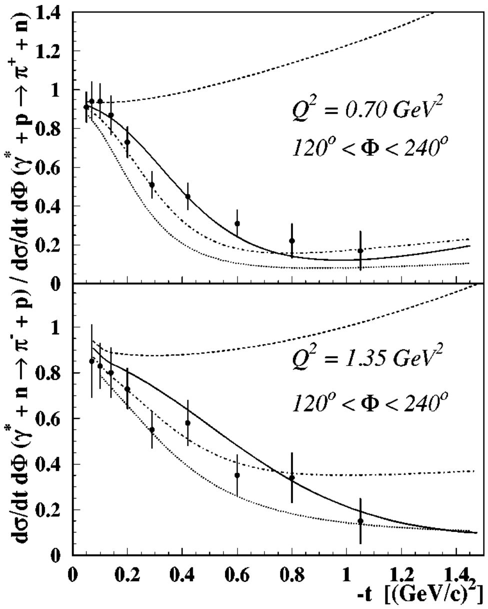

FIG. 2. Ratio of π^-/π^+ electroproduction on the nucleon at $W = 2.19$ GeV and $\varepsilon = 0.85$. Solid lines, $\pi+\rho$ Regge exchanges with $\Lambda_\pi^2 = \Lambda_\rho^2 = 0.462\ \mathrm{GeV}^2$; dash-dotted lines, $\pi+\rho$ Regge exchanges with $\Lambda_\pi^2 = 0.462\ \mathrm{GeV}^2$ and $\Lambda_\rho^2 = 2\ \mathrm{GeV}^2$; dashed lines, π Regge exchange with $\Lambda_\pi^2 = 0.462\ \mathrm{GeV}^2$; dotted lines, $\pi+\rho$ Born exchanges with $\Lambda_\pi^2 = \Lambda_\rho^2 = 0.462\ \mathrm{GeV}^2$. The data are from Ref. [9].

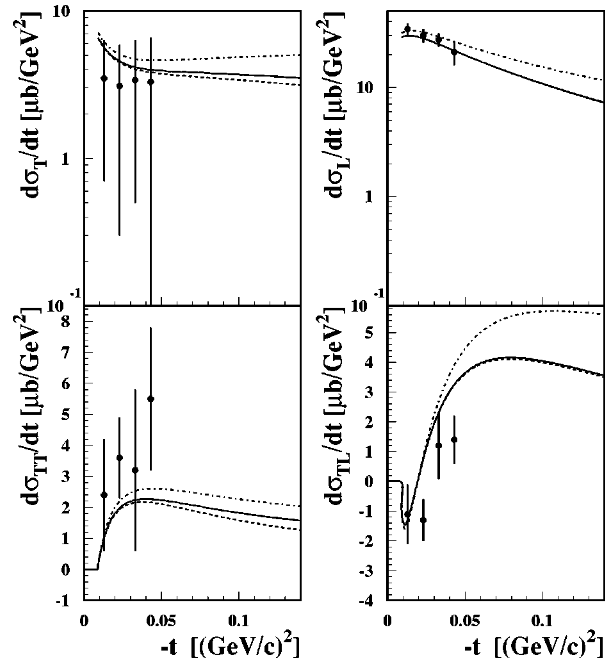

FIG. 3. T,L,TT, and TL response functions for π^+ electroproduction at $Q^2 = 0.35\ \mathrm{GeV}^2$ and $W = 2.1$ GeV. Solid lines, $\pi+\rho$ Regge exchanges; dashed lines, π Regge exchange; dash-dotted lines, π Born exchange. The data are from Ref. [11].

π and ρ Regge propagators [5,6] by the corresponding π and ρ Feynman propagators. For the π and ρ exchanges separately, the two models are equal at the pole of the exchanged particle. As already noticed in Ref. [8], a Born term model does not reproduce the t dependence of the cross section. The data at the highest energy $W = 3.1$ GeV clearly favor a Regge model: It predicts a much steeper t dependence at higher energy than a Born model. Even a Born model multiplied by a t-dependent off-shell form factor would not be able to describe this feature. At lower energy ($W = 2.15$ GeV), the t dependence is more comparable but the data also favor the Regge model. This steeper t dependence with increasing energy (Regge shrinkage) was clearly confirmed previously for photoproduction [5,6] where data exist at higher energy compared with the electroproduction data. Furthermore, it is seen in Fig. 1 that including a t-channel ρ Born exchange leads to a rising t behavior of the cross section at larger $-t$ values which is clearly ruled out by the data. Besides the different behavior in t, the Born model and Regge model lead to a different value of the extracted pion electromagnetic form factor. This difference is accentuated at larger Q^2 as discussed below.

Besides the π^+ cross sections, a decisive test of the pion photo and electroproduction models is the π^-/π^+ ratio, because this observable is fixed as soon as one has a model for π^+ photo and electroproduction. The π^-/π^+ ratio has always been difficult to describe in previous attempts. The new finding of Ref. [5] was that a good description of this observable for real photons is obtained by using degenerate π and ρ Regge trajectories with different phases (rotating phase for π^+ versus nonrotating phase for π^- due to G-parity considerations) and by the implementation of gauge invariance. As can be seen in Fig. 2, the Regge model is able to describe the t dependence of the virtual photon data for the π^-/π^+ ratio as well as was found previously for real photons, strongly confirming the relevance of the basic elements of the model. A comparison between the π Regge exchange and $\pi+\rho$ Regge exchanges also shows that the π^-/π^+ ratio is a sensitive observable to determine the relative weight of the ρ-exchange contribution. Note that, although the $\pi+\rho$ Born model prediction is not so bad for this observable, the t dependence of $d\sigma/dt$ in Fig. 1 clearly rules it out.

A good understanding of the role of ρ exchange in the charged pion electroproduction reaction is indispensable before one can reliably extract the π electromagnetic form factor. Alternatively, our Regge model which contains only two Regge exchange mechanisms holds also promise to access the $\rho\pi\gamma$ transition form factor once the π electromagnetic form factor is determined. To obtain a reliable extraction of these two form factors, a separation of the cross section into the various response functions is indispensable.

It is well known that the unpolarized π^+ electroproduction cross section (after removal of the virtual photon flux factor) can be decomposed into four response functions

$$2\pi \frac{d\sigma}{dt\,d\Phi} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} - \varepsilon \cos(2\Phi) \frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)} \cos(\Phi) \frac{d\sigma_{TL}}{dt}, \qquad (2)$$

where Φ is the out-of-plane angle and ε is the virtual photon polarization parameter. In Fig. 3, the T,L,TT, and TL response functions are shown for the latest available data at low Q^2 ($Q^2 = 0.35\ \mathrm{GeV}^2$) where the role of the pion electromagnetic form factor is rather small and where its value is rather well constrained due to a direct measurement by pion electron scattering [10]. A comparison of the different re-

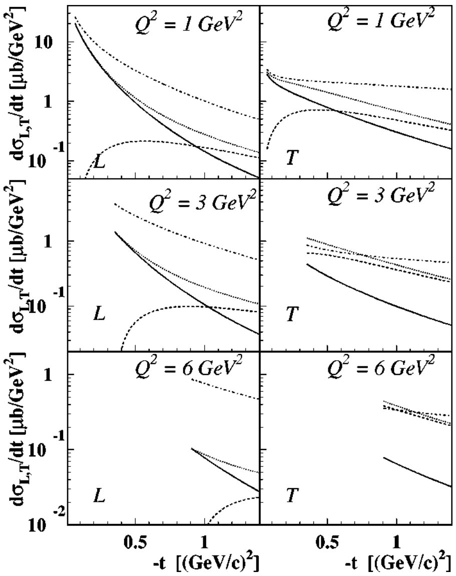

FIG. 4. T and L response functions for $\gamma^* + p \to \pi^+ + n$ at $W = 2$ GeV and for different values of Q^2. The first calculated point in $-t$ indicates the value $-t_{min}$. Solid lines, $\pi+\rho$ Regge exchange model with $\Lambda_\pi^2 = \Lambda_\rho^2 = 0.462$ GeV^2; dash-dotted lines, π Born exchange with $\Lambda_\pi^2 = 0.462$ GeV^2. The dotted lines represent the $\pi+\rho$ Regge exchange model with $\Lambda_\pi^2 = 0.462$ GeV^2 and $\Lambda_\rho^2 = 2$ GeV^2, and the dashed lines represent the ρ Regge exchange with $\Lambda_\rho^2 = 2$ GeV^2.

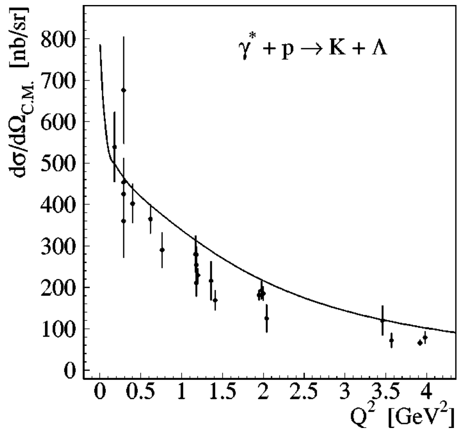

FIG. 5. Differential cross section for $\gamma^* + p \to K^+ + \Lambda$ at $W = 2.15$ GeV, $\varepsilon = 0.85$ and averaged over forward angles ($\theta_{c.m.} < 15°$). References to the data can be found in Ref. [17].

sponse functions shows that at this low Q^2 value, the longitudinal response function dominates at forward angles. Furthermore, the t dependence of the model for the L response function is much steeper than for the T response function. This is in agreement with the trend of the data. The model predictions for the interferences TT and TL are in reasonable agreement with the data. The separation with greater accuracy of the different response functions at higher values of Q^2 will become possible with the experiments at TJNAF [2,12,13].

In Fig. 4, the T and L cross sections for π^+ electroproduction are shown for typical values of Q^2 which will be taken around $W \approx 2$ GeV at TJNAF [2]. It is seen that the L response function is independent of the ρ exchange at $t = t_{min}$ (t_{min} corresponds to the value of t when the pion goes into the forward direction) which makes it appropriate to extract the π electromagnetic form factor. Going to higher Q^2, the value of $-t_{min}$ increases (for a given W) as can be seen in Fig. 4. Consequently, to extract the π electromagnetic form factor one has to extrapolate to the pion pole ($t = m_\pi^2$) which is farther away at these higher Q^2 values. Although the extrapolated value at the pion pole of a Born and Regge model gives the same result when the same form factor is used, it is seen once more in Fig. 4 that the t dependence is very different if one is farther away from the π pole. If the form factor fit has to be done using the data at higher t values, the extraction becomes more and more model dependent as one goes to larger Q^2 for a given W. This motivates one to go to higher energies because the value of $-t_{min}$ decreases. On the other hand, the Regge model better reproduces the t dependence of the available data and should be preferably used to extrapolate to the pion pole.

Once the π form factor is extracted from the L response function, one can use the sensitivity of the T response function to the ρ exchange. This is illustrated in Fig. 4 for two choices of the mass scale in the F_ρ of Eq. (1): $\Lambda_\rho^2 = 0.462$ GeV^2 and $\Lambda_\rho^2 = 2$ GeV^2. It is seen that the sensitivity to the $\rho\pi\gamma$ form factor at larger Q^2 is due to the finite contribution at $t = t_{min}$ of the ρ exchange to the T response function in contrast to the L response function where the ρ-exchange contribution vanishes at $t = t_{min}$ due to the $\rho\pi\gamma$ vertex structure at high energy. It was shown in Fig. 2 that the π^-/π^+ ratio provides quite a strong check of the ρ-exchange contribution which is well predicted by our gauge invariant $\pi+\rho$ Regge exchange model. It is also seen from Fig. 4 that the T response function is predicted to show a much less steep t dependence. This trend is already seen in the very few existing L/T separations performed in the 1970's at Cornell [14] and DESY [15] which are, however, not compatible [16] and show large uncertainties. The forthcoming experiments at TJNAF should provide accurate L/T separation for the pion electroproduction at intermediate values of Q^2. This opens up the prospect to extract at the same time the π electromagnetic form factor from the L response function and determine the $\rho\pi\gamma$ transition form factor from the T response function using the Regge model described in this paper.

The present model has also been applied in an exploratory way to the strangeness electroproduction reactions $\gamma^* + p \to K^+ + \Lambda$ and $\gamma^* + p \to K^+ + \Sigma^0$ at high energies, with the coupling constants determined from kaon photoproduction reactions [6]. Figure 5 shows the results for the $\gamma^* + p \to K^+ + \Lambda$ forward differential cross section as function of Q^2 around $W \approx 2.15$ GeV. A fair description is obtained using the monopole parametrization of Eq. (1) for the K and K^* form factors with $\Lambda_K^2 = \Lambda_{K^*}^2 = 0.6$ GeV^2. As the K and K^* Regge exchanges play a different role in the $\gamma^* + p \to K^+ + \Lambda$ and $\gamma^* + p \to K^+ + \Sigma^0$ reactions (the $K^+\Sigma^0$ reaction being dominated by K^* exchange), a study of both reactions can provide an additional lever arm to disentangle the kaon electromagnetic form factor and the $K^* K\gamma$ transition form factor. A more systematic comparison to strangeness electroproduction observables and to ongoing kaon electroproduction experiments at TJNAF [12,13] will be shown in a forthcoming article. The sparse available data set will be superseded by these ongoing experiments at TJNAF. The Regge model provides an economical way to analyze them and to extrapolate to the pion and kaon poles.

In summary, it was shown that a Regge model for charged pseudoscalar meson electroproduction above the resonance region is quite successful in describing available data and is therefore preferable compared with the more traditional Born models. It should be used to extract the pseudoscalar meson electromagnetic form factors at larger Q^2 and to quantify the transition from the nonperturbative to perturbative QCD regimes in these form factors.

We thank P. Guichon for useful discussions. This work was supported by the French Commissariat à l'Energie Atomique and in part by the EU/TMR Contract No. ERB FMRX-CT96-0008.

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