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Extraction of the πNN form factor from charged pion photoproduction

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The πNN form factor $F_{\pi NN}(t)$, at small values of the momentum transfer, $0<|t|\lesssim 0.3$ (GeV/c)^2, has been determined from an analysis of the experimental data on $\gamma p\to\pi^+ n$ for incident photon energies in the range 3.4–18 GeV. A total of 104 unpolarized differential cross sections and 22 asymmetries have been fitted with a Reggeized one-pion-exchange model. The best fits give for a monopole vertex function a range $\Lambda\approx 1000$ MeV and for a dual model type of form factor, an asymptotic rate parameter $\beta\approx 2.3$–2.5. These results are consistent with those of a recent analysis of NN charge exchange scattering data at high energy and the same range of momentum transfers. The contribution of non-one-pion exchanges to the photoproduction amplitudes has been found to be negligible and does not affect the χ^2, thus leading to an essentially model independent extraction of $F_{\pi NN}(t)$. The implications of these results for the construction of one-pion-exchange potentials in nuclear physics is briefly discussed.

[NUCLEAR REACTIONS Pion photoproduction on nucleons at high energies; extraction of the πNN form factor at small momentum transfers; the one-pion-exchange potential.]

I. INTRODUCTION

The pionic form factor of the nucleon, i.e., the πNN three-point function $F_{\pi NN}$ is known to play an important role in the NN interaction and considerable effort has been devoted in the past to the study of its analytic structure.[1] In fact, knowledge of the πNN form factor is crucial for the construction of NN potentials for low and intermediate energy scattering, and calculations of NN phase shifts through the iteration of one-pion exchange (OPE) are known to be sensitive to the range[2] as well as to the off-shell structure of $F_{\pi NN}$.[3] The three body force, some two to three body reactions such as $NN\to\pi NN$ and OPE in nuclear physics are also examples of processes that depend strongly on the πNN vertex function. On the other hand, the value of $F_{\pi NN}$ at zero momentum transfer is an important quantity related to the strength of chiral SU(2) $\times$ SU(2) symmetry breaking through the Goldberger-Treiman discrepancy.[4]

It has been customary to parametrize the πNN form factor by a monopole form[5] involving a single free parameter Λ, i.e.,

$$F_{\pi NN}(t)=\frac{\Lambda^2-\mu_\pi^{\;2}}{\Lambda^2-t}. \tag{1}$$

However, except for its simplicity, there has been little basis for such a choice. A much more general and physically motivated form that was suggested some time ago is that based on the dual model for three-point functions.[6,7] In this framework the πNN form factor is

$$F_{\pi NN}(t)=\Gamma(\beta)\frac{\Gamma[1-\alpha_\pi(t)]}{\Gamma[\beta-\alpha_\pi(t)]}, \tag{2}$$

where

$$\alpha_\pi(t)=\alpha'(t-\mu_\pi^{\;2}), \tag{3}$$

is the pion Regge trajectory with universal slope $\alpha'=\frac{1}{2}M_\rho^{\;2}\approx 0.83$ GeV^{-2} and β is a free parameter that governs the asymptotic behavior of $F_{\pi NN}$ in the spacelike region. Although as it stands Eq. (2) has poles on the real axis, it can be easily unitarized[7] without the undesirable implications that afflict the dual model for scattering amplitudes. Also, Eq. (2) can be generalized to describe any hadronic vertex with one, two or three particles off the mass shell.[3]

Another parametrization of $F_{\pi NN}$ that has been popular in Regge fits to high energy reactions is the exponential form factor.[8] However, large angle scattering data seem to indicate that form factors exhibit power rather than exponential asymptotic behavior in the momentum transfer, a feature predicted by the dual model[3] and also by the constituent interchange quark model (CIM).[9] In addition, an exponential form factor would imply exact SU(2) $\times$ SU(2) symmetry, and hence, the existence of zero mass pseudoscalar mesons (Goldstone bosons).

In any case, once a model or a parametrization of $F_{\pi NN}$ is adopted, e.g., Eqs. (1) or (2), the problem then becomes how to determine the range of the form factor, i.e., Λ or β, in the least model dependent fashion. One possibility, suggested by Chew[10] many years ago, is to extract $F_{\pi NN}(t)$ from an analysis of NN scattering data at high energy and small values of the momentum transfer, the idea being that in this kinematic region one expects the OPE contribution to dominate. In this spirit, a fit to the average of the differential cross sections for $\bar{p}p \to \bar{n}n$ and $np \to pn$ at $P_{\rm lab} = 8$ GeV/c has been carried out by Bongardt, Pilkuhn, and Schlaile.[11] The reaction average is taken in order to eliminate ρ-A_2 interference thus leaving basically two contributions, viz., the pion-Pomeron cut and the OPE. If the form factor is parametrized as in Eq. (1) the result of this analysis gives $\Lambda \sim 600$ MeV. More recently, Cass and McKellar[12] have reanalyzed the NN charge exchange data at $P_{\rm lab} = 8$ and 23.5 GeV/c using the dual model form Eq. (2) and have found $\beta \approx 6.5$. If Eq. (2) is expanded in power series near $t=0$ and approximated by a monopole form Eq. (1) this value of β implies a range compatible with the previous analysis. The problem is, however, that such a small value of Λ disagrees with results of dispersion theory calculations ($\Lambda \sim 1$ GeV) (Ref. 13) and such a large value of β is in contradiction with the asymptotic behavior of $F_{\pi NN}$ to be expected from the power counting rules of the CIM ($\beta \sim 3$).[3] There is also a contradiction with an analysis of NN pion production[14] although here the evidence is perhaps not as conclusive due to a higher degree of model dependence.

It was pointed out recently[15] that the reason for this discrepancy is the inadequate Regge behavior of the OPE contribution used in Refs. 11 and 12. In fact, when the pion pole is allowed to become a moving rather than a fixed pole at high energy according to the prescriptions of the orthodox Regge model, which is amply supported by experiment, then fits to NN charge exchange scattering data at $P_{\rm lab} = 5$, 8, and 25 GeV/c give[15] $\Lambda \approx 900$ MeV or $\beta \approx 3$ for Eqs. (1) and (2), respectively. It should be noted that if $\beta > 2$ Eq. (2) predicts that $F_{\pi NN}$ will have a faster asymptotic fall off than that given by the monopole form Eq. (1). For small values of the momentum transfer, however, Eq. (1) provides an excellent approximation to Eq. (2) and, in fact, the fits mentioned above give basically the same χ^2 for both models.

Due to the key role played by the πNN vertex function in intermediate energy, as well as in nuclear physics, it is essential to corroborate these results through the study of additional reactions where the OPE contribution dominates and where the extraction of $F_{\pi NN}$ involves the minimum amount of model dependency. One such reaction, to which we address ourselves in this paper, is charged pion photoproduction, i.e., $\gamma p \to \pi^+ n$. This process exhibits striking similarities with NN charge exchange since it is known[16,17] to be dominated at high energy and small momentum transfers by the pion pole and a slowly varying background (e.g., π-Pomeron cut). At first sight, though, it seems that $F_{\pi NN}$ would have to appear only once in the OPE amplitude for $\gamma p \to \pi^+ n$ in contrast with NN scattering where it contributes to both vertices in the crossed channel. However, since the exchanged pion is off the mass shell one would expect, *a priori*, some structure on both the $\gamma\pi\pi$ and πnp vertices (see Fig. 1). In fact, it has been shown in Ref. 3 that in the framework of the dual model any three-point function $F(P_1^2, P_2^2, P_3^2)$ factorizes, i.e.,

$$F(p_1^2, p_2^2, p_3^2) = g \prod_{i=1}^{3} \Gamma(\beta_i - s_i) \times \frac{\Gamma[1-\alpha'(p_i^2 - M_i^2)]}{\Gamma[\beta_i - s_i - \alpha'(p_i^2 - M_i^2)]}, \tag{4}$$

where s_i is the spin of the particle with four momentum P_i and mass M_i, the β_i are three free parameters (one for each distinct leg), and g is an overall normalization or coupling constant fixed at the fully on-shell point, i.e.,

$$g = F(P_1^2 = M_1^2, P_2^2 = M_2^2, P_3^2 = M_3^2). \tag{5}$$

As a consequence of these considerations the form factor $F_{\gamma\pi\pi}$ $(k^2=0, q^2=\mu_\pi^2, t)$ should be the same as the πNN form factor $F_{\pi NN}(P_i^2 = M^2, P_f^2 = M^2, t)$ except for an overall normalization constant defined at the fully on-shell point (the electric charge for $F_{\gamma\pi\pi}$ and the strong coupling constant for $F_{\pi NN}$). This result then enhances the similarities be-

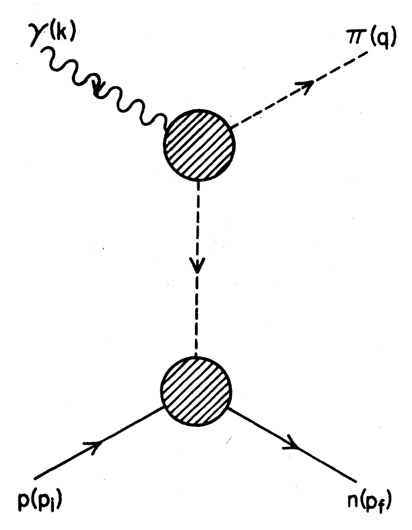

FIG. 1. The one-pion exchange (OPE) and kinematics for $\gamma p \to \pi^+ n$. The blobs at each vertex indicate the presence of a form factor due to the off-shell nature of the exchanged pion (see text).

tween pion photoproduction and NN charge exchange scattering.

In addition, there are two other advantages for the $\gamma p \to \pi^+ n$ reaction when compared with NN. First, a very large number of differential cross section measurements for unpolarized photons over a wide range of energies and second, the availability of experimental data for the asymmetry found in $\gamma p \to \pi^+ n$ with the incident photons linearly polarized parallel and perpendicular to the plane of πN production. This second feature allows a separation of the natural and unnatural parity exchange contributions in the t channel[18] and thus the isolation of the OPE. Furthermore, it is known from this as well as from other reactions that asymmetry information places stringent constraints on theoretical models, i.e., a model that gives a reasonable fit to unpolarized cross sections might fail completely to account for the polarization data.

Another well known constraint in pion photoproduction is that imposed by gauge invariance which leads to constraint theorems in all channels having a Born term.[19] An example of a model that satisfies this constraint is the so called electric Born approximation which takes into account the t-channel pion pole together with those contributions from the s- and u-channel nucleon poles required for gauge invariance but without any form factor at the vertices.[17] Since our extraction of $F_{\pi NN}$ will be based on a fully Reggeized one-pion exchange with form factors, it will be important to verify that the constraints imposed by gauge invariance[19] are still satisfied. It is easy to see that this will be the case due to (i) the factorization property of the dual model for three-point functions and (ii) the fact that once the overall coupling constant has been extracted from the form factor the remainder is normalized to one at the pole [see Eq. (4)]. Thus, the residues of the Born terms in the various channels are not affected by dressing the one particle exchanges and therefore the relations among these residues imposed by gauge invariance will not be modified.

In Sec. II we define the helicity amplitudes, cross sections, and asymmetry and, by means of the evasive constraint,[17] identify the amplitudes to which the OPE and the slowly varying background contribute. Since our purpose here is not to make a Regge fit to the data, *per se*, to add to a by now extensive list,[20] but rather to extract the πNN form factor we shall keep the parametrization of this background as simple as possible. In fact, we shall avoid any detailed dynamical model for the cut and simply assume a modified "poor man's" absorption model[16] where the background is parametrized as an exponential. This has been a standard procedure in this type of analysis and will establish a one to one correspondence with the results already obtained from NN charge exchange scattering.

In Sec. III we discuss the results of simultaneous fits to the unpolarized differential cross sections and asymmetries at various photon energies in the range 3.4–18 GeV and momentum transfers $0<|t|<0.3$ (GeV/c)^2. Our results give $\Lambda = 1003 \pm 66$ MeV for a monopole form factor Eq. (1), or $\beta = 2.34 \pm 0.23$ for the dual model Eq. (2), with an identical $\chi^2 = 289$ for a total of 126 data points. The sensitivity of the data to the presence of a πNN form factor has been established by attempting fits with $F_{\pi NN} = 1$ in which case the best fit χ^2 is increased to $\chi^2 = 411$ for the same number of data points. On the other hand, the presence of contributions other than the OPE and the pion cut has been studied by adding a Reggeized ρ-A_2 exchange with electric and magnetic residue functions. The results of the search show that this extra contribution is negligible in the range of momentum transfers covered by the fit and does not affect the form factor or the χ^2, i.e., $\Lambda = 1023 \pm 65$ MeV and $\chi^2 = 287$. These results are compatible with those obtained from NN charge exchange scattering and provide an important independent confirmation of theoretical expectations pointing to a range of the πNN vertex function of the order of 1000 MeV or an asymptotic rate parameter $\beta \approx 2-3$.

In the conclusion we discuss briefly the implications of these results for the Goldberger-Treiman discrepancy.

II. KINEMATICS AND REGGEIZATION

In the direct or s channel for $\gamma p \to \pi^+ n$ there are four independent center of mass helicity amplitudes[21] $g_i(s,t) = g_{0\lambda';\lambda_\gamma\lambda}$, where $i = 1, 2, 3, 4$ stands for the photon, initial nucleon, and final nucleon helicities

$$(\lambda_\gamma, \lambda_N; \lambda_N') = (-1, -\tfrac{1}{2}; \tfrac{1}{2}), (1, -\tfrac{1}{2}; -\tfrac{1}{2}), (1, \tfrac{1}{2}; \tfrac{1}{2}), (1, -\tfrac{1}{2}; \tfrac{1}{2}),$$

respectively. In terms of these amplitudes the cross sections can be written as[21]

$$(s-M^2)^2 \frac{d\sigma_\parallel}{dt} = \frac{1}{32\pi}\left(|g_2 - g_3|^2 + |g_1 - g_4|^2\right), \tag{6}$$

for photons polarized parallel to the reaction plane, and

$$(s-M^2)^2 \frac{d\sigma_\perp}{dt} = \frac{1}{32\pi}\left(|g_2 + g_3|^2 + |g_1 + g_4|^2\right), \tag{7}$$

for photons polarized perpendicular to the reaction plane. The unpolarized cross section is just the average of the preceding two, i.e.,

$$\frac{d\sigma}{dt}=\frac{1}{2}\left(\frac{d\sigma_{\parallel}}{dt}+\frac{d\sigma_{\perp}}{dt}\right),$$

or in its normal form,

$$(s-M^2)^2\frac{d\sigma}{dt}=\frac{1}{32\pi}\sum_{i=1}^{4}|g_i|^2\,. \tag{8}$$

In Eqs. (6)–(8), $s=(k+p_i)^2$ is the square of the center of mass energy in the direct channel and $t=(q-k)^2$ is the square of the momentum transfer. The asymmetry in pion photoproduction with linearly polarized photons is defined as

$$\Sigma=\frac{\dfrac{d\sigma_{\perp}}{dt}-\dfrac{d\sigma_{\parallel}}{dt}}{\dfrac{d\sigma_{\perp}}{dt}+\dfrac{d\sigma_{\parallel}}{dt}}. \tag{9}$$

The relation between the s-channel helicity amplitudes and the traditional Chew-Goldberger-Low-Nambu (CGLN) invariant amplitudes[22] $F_i(s,t)$ is given by

$$g_1=\frac{\nu}{\sqrt{2}}\left(\frac{t}{2M}F_1-\frac{2M}{\mu_\pi^2-t}F_2+F_3\right), \tag{10}$$

$$g_2=\frac{\nu}{\sqrt{2}}\left(\sqrt{-t}F_1+\frac{\sqrt{-t}}{2M}F_3+2M\sqrt{-t}F_4\right), \tag{11}$$

$$g_3=\frac{\nu}{\sqrt{2}}\left(-\sqrt{-t}F_1+\frac{\sqrt{-t}}{2M}F_3-2M\sqrt{-t}F_4\right), \tag{12}$$

$$g_4=\frac{\nu}{\sqrt{2}}\left(\frac{t}{2M}F_1+\frac{2M}{\mu_\pi^2-t}F_2+F_3\right), \tag{13}$$

where $\nu\approx(s-M^2)/2M$ is the laboratory photon energy. Since the invariant amplitudes $F_i(s,t)$ are free of kinematic singularities Eqs. (11) and (12) imply that g_2 and g_3 vanish identically at $t=0$. Furthermore, from the "conspiracy relation"[17] for pion photoproduction, i.e.,

$$F_2(t=0)=-\frac{\mu_\pi^2}{2M}F_3(t=0) \tag{14}$$

it follows that g_4 also vanishes at $t=0$. Therefore, the pion-Pomeron cut (or slowly varying background), which clearly does not vanish at $t=0$ where it is responsible for all of the cross section, can contribute only to the amplitude g_1. On the other hand, F_1 and F_3 contain natural spin-parity exchange while F_2 and F_4 have unnatural spin-parity exchanges. Neglecting A_1 exchange gives $F_4=0$ and therefore $g_2=g_3$ so that finally one has

$$g_1(s,t)=g_\pi(s,t)-g_A(s,t)-C_\pi(t)\,, \tag{15}$$

$$g_2(s,t)=g_3(s,t)=h_A(s,t)\,, \tag{16}$$

$$g_4(s,t)=-g_\pi(s,t)-g_A(s,t)\,, \tag{17}$$

where $C_\pi(t)$ is the slowly varying background, g_π the OPE, and g_A and h_A the ρ-A_2 exchange amplitudes. The Reggeized expression for the dressed OPE amplitude is[21]

$$g_\pi(s,t)=-eg_{\pi NN}\frac{t}{\mu_\pi^2-t}\{1+\exp[-i\pi\alpha_\pi(t)]\}\times\left(\frac{s}{s_0}\right)^{\alpha_\pi(t)}F_{\pi NN}{}^2(t)\,, \tag{18}$$

where $e=(4\pi/137)^{1/2}$, $g^2{}_{\pi NN}/4\pi=14.28$, $\alpha_\pi(t)$ the pion Regge trajectory Eq. (3), $s_0\approx1\ \text{GeV}^2$ a scale factor, and $F_{\pi NN}(t)$ the πNN form factor which appears squared according to the discussion in Sec. I. Similar expressions can be written for $h_A(s,t)$ and $g_A(s,t)$ including electric and magnetic couplings although we would expect their contributions to be negligible at small t due to their nonleading behavior. In fact, the effect of the pole will be less important and the A_2NN form factor will provide further damping. This expectation has been fully confirmed by the results of our fits to be discussed in the next section.

Parametrizing the background amplitude with an exponential form and using Eq. (18), the differential cross sections for OPE plus pion cut become

$$(s-M^2)^2\frac{d\sigma_{\parallel}}{dt}=\frac{e^2}{2}\frac{(g_{\pi NN}{}^2)}{4\pi}\left|Ae^{bt}+\frac{t}{\mu_\pi^2-t}\{1+\exp[-i\pi\alpha_\pi(t)]\}\left(\frac{s}{s_0}\right)^{\alpha_\pi(t)}F_{\pi NN}{}^2(t)\right|^2, \tag{19}$$

$$(s-M^2)^2\frac{d\sigma_{\perp}}{dt}=\frac{e^2}{2}\frac{(g_{\pi NN}{}^2)}{4\pi}\left|Ae^{bt}\right|^2. \tag{20}$$

For $A=1$ and $b=0$ Eqs. (19) and (20) reduce to the "poor man's" absorption model of Ref. 16. The parametrization of the cut was given no energy dependence beyond the overall factor of $(s-M^2)$ since the experimental cross sections in the forward direction obey the $1/s^2$ scaling law. At $t=0$ the unpolarized differential cross section is

$$(s-M^2)^2\frac{d\sigma}{dt}\bigg|_{t=0}=255A^2\ \mu\text{b GeV}^2\,, \tag{21}$$

and at the pion pole it becomes

$$(\mu_\pi^2-t)^2(s-M^2)^2\frac{d\sigma}{dt}\bigg|_{t=\mu_\pi^2}=255(2\mu_\pi^4)\ \mu\text{b GeV}^2\,, \tag{22}$$

which, except for the presence of A in Eq. (21), are the same results one obtains from the electric Born model. Since this model is known to predict roughly the correct value of the forward cross section, we would expect A to be close to one. Away from $t=0$, however, the Reggeized and dressed OPE model with absorption that we are considering should provide an improved description of the data. For values of t very near the forward direction, e.g., $|t| \lesssim 0.05-0.1$ $(\mathrm{GeV}/c)^2$, the interplay between the cut and the pion pole will be responsible for the forward spike in $d\sigma/dt$ and the rapid rise in the asymmetry with $F_{\pi NN}$ playing almost no role. At higher values of the momentum transfer, however, the data should be more sensitive to the range of the πNN form factor.

In summary, there are three free parameters in this model, i.e., A, b, and β (or Λ) and two independent sets of experimental data, viz., the unpolarized differential cross sections and the asymmetry. As mentioned previously, though, the presence of other non-OPE terms in the amplitudes, e.g., ρ-A_2 exchange, should also be tested in which case there will be two additional parameters; these additions should increase in importance as the value of $|t|$ increases.

III. FITS

We have used all the available data[23] above $\nu=3.4$ GeV measured at SLAC, DESY, and Cambridge Electron Accelerator (CEA), i.e., unpolarized differential cross sections[24-29] between $\nu=3.4$ and 18 GeV and asymmetries[29, 30-32] in the range $\nu=3.4-16$ GeV. Restricting ourselves to the interval $0<|t|\leq 0.3$ $(\mathrm{GeV}/c)^2$ we have used a total of 126 data points of which 104 were differential cross sections and 22 were asymmetries. The results of the fits with the OPE model with absorption are listed in Table I. As expected, the addition of non-OPE contributions to the amplitudes, e.g., ρ-A_2 exchange, did not change the results; we found $A=1.104\pm 0.004$, $b=1.29\pm 0.04$ $(\mathrm{GeV}/c)^{-2}$, and $\Lambda=1023\pm 65$ MeV with a $\chi^2=287$. In this case the strength of the ρ-A_2 contribution at the highest energy and highest momentum transfer (where it should be largest) was suppressed relative to OPE by roughly two orders of magnitude.

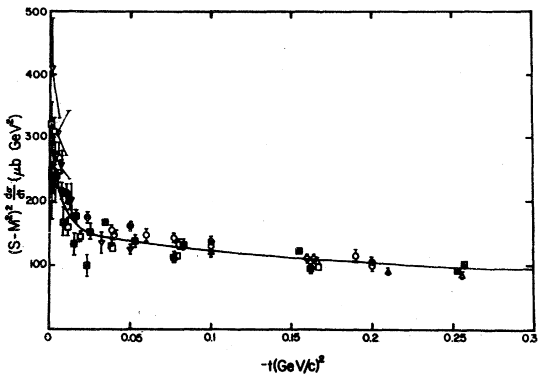

FIG. 2. Unpolarized differential cross sections for various incident photon energies. ● DESY, 3.4 GeV (Ref. 24); ○ SLAC, 5 GeV (Refs. 27 and 28); ▲ DESY, 6 GeV (Refs. 24–26); △ SLAC, 8 GeV (Refs. 27 and 28); □ SLAC, 11 GeV (Refs. 27 and 28); ■ SLAC, 16 GeV (Refs. 27–29); ▽ SLAC, 18 GeV (Ref. 28). Only a part of the data is shown. The solid curve represents the best fit with the Reggized OPE model with absorption and form factors (see Table I).

The sensitivity of the parameters A, b, and β (or Λ) to the range of momentum transfers covered by the fits was analyzed by refitting the data in different intervals, with the result that the values listed in Table I ($0<|t|<0.3$ $(\mathrm{GeV}/c)^2$) gave essentially the lowest χ^2. For instance, for a range $0<|t|<0.2$ $(\mathrm{GeV}/c)^2$ we found $A=1.090\pm 0.004$, $b=1.19\pm 0.01$ $(\mathrm{GeV}/c)^{-2}$, and $\Lambda=848\pm 12$ MeV with a $\chi^2=298$ for 117 degrees of freedom, while for $0<|t|<0.45$ $(\mathrm{GeV}/c)^2$ we found $A=1.109\pm 0.004$, $b=1.43\pm 0.02$ $(\mathrm{GeV}/c)^{-2}$, and $\Lambda=1790\pm 180$ MeV with a $\chi^2=449$ for 139 degrees of freedom.

Since the number of experimental differential cross sections is much larger than the number of asymmetries and most of the measurements of the latter have been done at $\nu=3.4$ and 16 GeV, we have also run fits to $d\sigma/dt$ and Σ at these two energies and $|t|<0.3$ $(\mathrm{GeV}/c)^2$ in order to check the stability of the results. We found in this case that $A=1.118\pm 0.009$, $b=1.33\pm 0.06$ $(\mathrm{GeV}/c)^{-2}$, and $\Lambda=1210\pm 160$ MeV with a $\chi^2=131$ for 45 degrees

TABLE I. Parameter values from fits to pion photoproduction differential cross sections and asymmetries. 126 data points − 3 parameters = 123 degrees of freedom.

Form factor	χ^2	Λ (MeV)	β	A	b $[(\mathrm{GeV}/c)^{-2}]$
Monopole	289	1003 ± 66		1.103 ± 0.004	1.34 ± 0.03
Dual model	289		2.34 ± 0.23	1.104 ± 0.004	1.35 ± 0.03
No form factor	411	∞	2	1.105 ± 0.005	1.43 ± 0.05

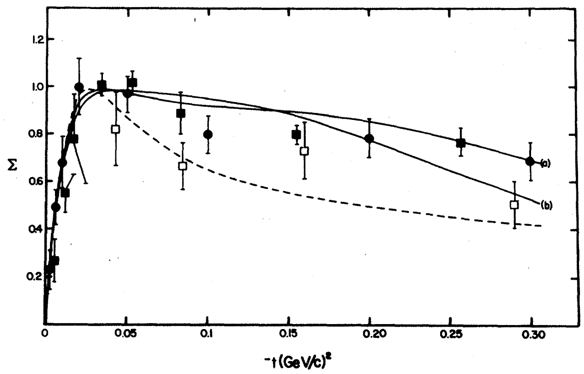

FIG. 3. Asymmetries at various incident photon energies. ● DESY, 3.4 GeV (Refs. 30 and 31); □ SLAC, 12 GeV (Ref. 32); ■ SLAC, 16 GeV (Ref. 29). Only part of the data is shown. Solid curves represent the best fit with the Reggeized OPE model with absorption and form factors. Curve (a) is for $\nu = 3.4$ GeV and curve (b) is for $\nu = 16$ GeV showing the energy dependence of the Reggeized OPE. The dotted curve is the best fit with no form factors ($\Lambda = \infty$ or $\beta = 2$) at $\nu = 3.4$ GeV (see Table I).

of freedom.

Our predictions from Table I are illustrated in Figs. 2 and 3 where only part of the data has been shown due to the high degree of overlap and clustering especially near the forward direction. The Reggeized OPE model has some energy dependence besides the overall $(s - M^2)$ factor which is much more pronounced in Σ as seen in Fig. 3; the differential cross section curves for the different energies cannot be resolved with the scales used in Fig. 2. The impact of the πNN form factor is best seen in the prediction for the asymmetry with $\Lambda = \infty$ or $\beta = 2$ (dotted curve) at $\nu = 3.4$ GeV, although the value of χ^2 in this case speaks for itself.

In summary, our results point to a range of the πNN vertex function $\Lambda \approx 1000$ MeV or $\beta \approx 2.3-2.5$ in agreement with the recent fit to NN charge exchange scattering[15] as well as with other more model dependent extractions[2,14] and theoretical expectations.[6,7,13]

IV. CONCLUSIONS

The similarities between NN charge exchange scattering and pion photoproduction provide us with the opportunity of verifying the overall consistency of the πNN form factor extraction. Moreover, the availability of two independent sets of experimental data, i.e., unpolarized cross sections and asymmetries, places more constraints on the parametrization of the $\gamma p \to \pi^+ n$ reaction giving us a more stringent test. On the other hand, at small momentum transfers the slowly varying background amplitude can be easily parametrized and all other non-OPE contributions are expected to be negligible, making the determination of $F_{\pi NN}$ essentially model independent.

Our results indicate a range of the πNN form factor $\Lambda \approx 1000$ MeV for a monopole parametrization Eq. (1), or an asymptotic rate parameter $\beta \approx 2.3-2.5$ for the dual model, consistent with the results of a recent NN charge exchange analysis.[15]

Although the χ^2 was identical for both models, it should be realized that they predict different asymptotic behaviors in the spacelike region; the monopole form behaves like t^{-1} while the dual model behaves like $t^{1-\beta}$ as $t \to -\infty$. The question then becomes which model should be trusted more in applications where a knowledge of $F_{\pi NN}$ in a wider range of t is needed, e.g., in the iteration of OPE in the Blankenbecler-Sugar equation for NN scattering. We argue in favor of the dual model due to its sound physical motivation based on the most successful features of the Regge and dual models, e.g., correct asymptotic power behavior and mass spectra. It should also be added that when used to describe electromagnetic and weak vertices[33] this model is in excellent agreement with experimental data in a very wide range of momentum transfers, e.g., up to $t \approx -30$ $(\mathrm{GeV}/c)^2$ for the magnetic form factor of the nucleon.

As a final point we wish to comment on the implications of our results for the Goldberger-Treiman discrepancy, i.e.,

$$\Delta_\pi = 1 - \frac{(M_p + M_n) g_A}{2 f_\pi g_{\pi NN}},$$

where g_A and f_π are the β decay and pion decay constants, respectively. This quantity is of great theoretical interest since it is a direct measure of the strength of chiral $SU(2) \times SU(2)$ symmetry breaking, i.e., the mechanism that explains the smallness of the pion mass on a hadronic scale.[4] The πNN form factor at zero momentum transfer is related to Δ_π through[4]

$$F_{\pi NN}(t=0) = 1 - \Delta_\pi .$$

One of the arguments invoked in the past in favor of a very short range πNN interaction was based precisely on this equation. In fact, the experimental value of Δ_π used to be $\approx 15\%$ implying a range $\Lambda \approx 400$ MeV for a monopole form factor. However, the actual value of Δ_π is far from settled and has been gradually decreasing as new determinations of $g_{\pi NN}$ and g_A become available. Using the latest compilation of coupling constants[34] one has at the present time: $f_\pi = 93.24 \pm 0.09$ MeV, $g_{\pi NN}{}^2/4\pi = 14.28 \pm 0.18$, and $g_A = 1.260 \pm 0.012$, giving for Δ_π

$$\Delta_\pi = 0.05 + 0.01\,,$$

where the error should be handled with extreme care in view of the historic evolution of Δ_π. Using $\Lambda \approx 1000$ MeV or $\beta \approx 2.3 - 2.5$ from Table I we find $\Delta_\pi \approx 0.02$ in both cases. This result agrees with independent estimates based on dispersion theory calculations of the matrix elements of the divergence of the axial-vector current in β decay[35] as well as with various other theoretical estimates.[6,7,36] In order to obtain $\Delta_\pi \approx 0.05$ we would need a range $\Lambda \approx 600$ MeV or an asymptotic rate parameter $\beta \approx 10$, which are ruled out by the present analysis of pion photoproduction and by the NN charge exchange results.[15] Moreover, if $\beta = 10$ then the πNN form factor would behave like t^{-9} as $t \to -\infty$, clearly an inconceivable situation.

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