Deuteron photodisintegration, quark-gluon string model, and Regge phenomenology

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We have derived an expression for the cross section for the $\gamma d \rightarrow pn$ reaction at small momentum transfers t and u in the framework of the quark-gluon model and Regge phenomenology. Our predictions reproduce very well the few data available at energies between 1.5 and 4.2 GeV, where our approach can be applied. Moreover, we found a good agreement also with the forward- and backward-angle data in the intermediate-energy region.

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I. INTRODUCTION

The experimental identification of quark effects in nuclei would constitute an important progress towards the understanding of the nucleus in terms of fundamental strongly interacting particles and would clarify the mechanisms underlying the transition from the nucleonic degrees of freedom to the quantum chromodynamics (QCD) based description of the nucleus. In this respect, the study of deuteron with electromagnetic probes of high (and, maybe, intermediate) energies has very interesting features. In fact, the deuteron is the simplest nucleus and allows the best separation of nuclear structure ambiguities from reaction mechanism ambiguities.

In the framework of conventional nuclear physics, the deuteron photodisintegration amplitude is treated in terms of nucleon and meson degrees of freedom in the deuteron wave function using the mechanism of pole and triangle graphs described in Ref. [1] with the account of final-state interactions. The inclusion of the meson exchange currents, Δ-resonance contribution, and relativistic effects has led to a reasonable description of the total cross section below 400 MeV, though at present there are no calculations available which describe the whole set of experimental information.

At higher energies the uncertainties of conventional models become larger as expected because of the opening of multipion photoproduction channels and the more essential role of the relativistic effects [1,2]. Moreover, it is not clear whether the conventional theory with nucleon, meson, and isobar degrees of freedom alone will be able to describe the experimental results or some other basic ingredients (like quark-gluon degrees of freedom) are of fundamental importance [3,4]. This would not be surprising, since at energies above the Δ region the wavelength of the photon becomes comparable to the expected distance between quarks in the nucleus.

Therefore, in recent years the interest has shifted towards probing possible quark and gluon degrees of freedom, and the efforts have focused on extending meson-exchange calculations to higher-energy scales [2], and QCD to lower-energy scales [3], to see which gives a better description of experimental data. In this scheme, it is clear that the energy region between a few hundred MeV and a few GeV can provide the very interesting possibility of investigating the transition from the conventional nuclear physics description to the quark-gluon description based on QCD or QCD-inspired models.

In this paper we will apply the quark-gluon string (QGS) model [5] and Regge phenomenology to the reaction $\gamma d \rightarrow pn$ in the region of small momentum transfers t or u. (Here t, u, and s are the usual Mandelstam variables.) In Sec. II we discuss the general properties of the QGS model as a microscopic model of the Regge phenomenology [6], and we present the arguments why the QGS model and Regge phenomenology can be used for exclusive reactions with nuclei, and why it can be extrapolated to the energy below 1 GeV. In Sec. III we derive an expression for the forward and backward cross section for the $\gamma d \rightarrow pn$ reaction in the framework of this model and we discuss the choice of the parameters. In Sec. IV we compare the predictions of the model to the recent data obtained by the NE17 experiment at SLAC [7] in an energy region (1.1–4.2 GeV) where our approach is valid, and we also discuss the fit to the forward- and backward-angle data available at 375–700 MeV [8–10] used to determine with low uncertainties the parameters of the QGS model.

II. REGGE PHENOMENOLOGY AND THE QUARK GLUON STRING MODEL

The necessary condition for using the Regge phenomenology is the absence of resonance structures in the cross sections. In nuclei the nucleon resonances are broadened and damped [11], then the region of applicability of the Regge phenomenology might be wider for photonuclear than for photonucleon reactions.

In the case of the deuteron photodisintegration, the major feature of the total and differential cross sections is a smooth falloff with energy above an incident photon en-

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ergy of 5 MeV, except for the prominent Δ peak at approximately 280 MeV. Then, the Regge approach might be applied to this reaction starting from about few hundred MeV energy.

Then, let us look at the deuteron photodisintegration with the high-energy-physicist eye and try to extrapolate this point of view to the intermediate energy region. At high energy, it is convenient to distinguish two different kinematical regions: (i) high momentum transfers [$t \gg 1$ (GeV/c)^2], and (ii) small momentum transfers [$t \leq 1$ (GeV/c)^2].

In region (i) according to quark-dimensional counting rules, the cross section of the reaction at constant center-of-mass angle $\vartheta_{\text{c.m.}}$ should be a very fast decreasing function of energy [3]:

$$\frac{d\sigma}{dt}(\vartheta_{\text{c.m.}}=\text{const}) \sim s^{-11} . \tag{1}$$

In region (ii), that is at sufficiently high energy and small t or u, the photodisintegration amplitude is dominated by the exchange of three valence quarks in t or u channels [see Fig. 1(a)] with any number of gluons exchanged between them. In the framework of $1/N_c$ expansion in QCD (where N_c is the parameter of the color gauge group), this is the consequence of the dominance of the planar-quark-gluon graphs. This expansion was first considered by t' Hooft [12], who proposed to analyze the properties of non-Abelian quantum field theory in the large N_c limit. Then, the behavior of different quark-gluon graphs according to their topology was discussed by Rossi and Veneziano [13]. Later on, Kaidalov [5] proposed the QGS model to describe different binary reactions at high energy. This model is based on the properties of $1/N_f$ expansion in QCD (where N_f is the number of flavors), and can be considered as a microscopic model of the Regge phenomenology. In the limit of large N_f the simplest planar-quark-gluon graphs give the dominant contributions into the amplitudes of binary reactions. In the space-time representation these graphs are described by a formation of a quark-gluon string in the

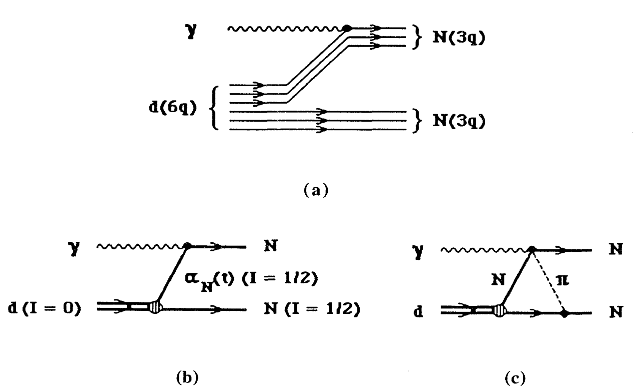

FIG. 1. (a) The three-quark-exchange diagram which dominates the deuteron photodisintegration amplitude at sufficiently high energy and small t or u. (b) In the Regge language this contribution corresponds to the exchange of the Reggeon $\alpha_N(t)$. At large energies the diagram of (b) includes the contribution of the graph (c), which describes the photoproduction on a nucleon.

intermediate state. This quark-gluon string can be identified with the corresponding Regge trajectory. In the Regge language, the dominant contribution of three-quark exchange corresponds to the fermion Regge pole [see Fig. 1(b) where the line $\alpha_N(t)$ describes the exchange of a Reggeon, which is an assembly of three quarks plus many gluons with angular momentum $\alpha_N(t)$]. Let us note that at large energies and small t the diagram of Fig. 1(b) includes the contribution of the graph of Fig. 1(c): the amplitude $\gamma N \rightarrow \pi N$ in Fig. 1(c) can be described by the Regge-pole exchange and the triangle can be included into the vertex $d \rightarrow N + \text{Reggeon}$. In the resonance region, $E_\gamma \leq 1$ GeV, when the local correspondence between the Regge and the resonance amplitude is absent, the contribution of the diagram in Fig. 1(c) cannot be incorporated completely into the amplitude corresponding to the diagram in Fig. 1(b). This statement is also true for large t when the amplitude $\gamma N \rightarrow \pi N$ cannot be described by the Regge exchange. The vertex $d \rightarrow N + \text{Reggeon}$ cannot be described only by the nucleon degrees of freedom in the deuteron and contains essential contributions from non-nucleonic components and, in particular, from the six-quark bag admixture in the deuteron wave function [14].

The QGS model gives new important insights into the Regge phenomenology. It can explain, for example, the quark-gluon content of different Reggeons, relate their residues, predict inclusive spectra of different particles in different kinematical regions, find the relations between exclusive and multiple production amplitudes through the unitarity conditions, etc. The Regge-pole analysis of the exclusive hadronic reactions (see, e.g., Ref. [6]) was formulated much before the fundamental theory of strong interactions (QCD) was discovered. Nevertheless, all its phenomenological applications remain valid, because it is based on fundamental properties of scattering amplitudes such as analyticity, unitarity, and crossing symmetry. Despite the very broad applications of such approaches to the different hadronic reactions and to the inclusive hadron-nucleus collisions at rather high energy, they were poorly used in the description of exclusive reactions with nuclear targets. One of the main reasons is apparently related to the fact that those approaches were originally introduced to describe high-energy data, but data on exclusive reactions with nuclear targets have been limited, up to now, mainly to the intermediate-energy region.

Let us say something more on the region of validity in s and t of this approach. From the quantum-mechanical point of view, high energy means that the wavelength of the photon is much smaller than the radius of the target; that is, $\lambda \sim 1/E_\gamma \ll R_0$. In the QCD the value of R_0 is equal to the radius of confinement, which is about 1 fm. Therefore, the necessary condition $E_\gamma R_0 \gg 1$ can be considered as fairly satisfied in the intermediate-energy region $E_\gamma \geq 1$ GeV.

In the Regge phenomenology [6], high energy means $s \gg t_{\text{char}}$, where t_{char} is some characteristic value of t which is usually taken to be ~ 1 (GeV/c)^2.

As far as the region of validity in t (or u) is concerned, there is a common convention that this is limited by $|t|$

(or $|u|$) ≤ 1 (GeV/c)^2. This convection is based on the consideration that with increasing of $|t|$ (or $|u|$) the secondary singularities in the complex angular momentum plane (like daughter Regge poles or branch points) may also become important. However, this consideration cannot be formulated in a quantitative way because the residues of Regge poles and discontinuities of Regge cuts are usually parametrized and are different for different reactions. This means that the phenomenological descriptions of data include contributions of some effective Regge trajectories which in turn may include the contributions of secondary singularities. In this case the fit of some data can be achieved even for larger values of $|t|$.

A different philosophy can be used in the QGS model. Each graph in this model is classified according to its topology and the corresponding Regge singularity is fixed by the quark-content of the graph. Therefore, the amplitude corresponding to this graph can be considered for all values of s and t as an analytic function of those variables. Using correspondence with the Regge phenomenology, we can conclude that in our case the graph of Fig. 1(a) with three-quark exchange will be dominant at large energies, $s \gg t_{\mathrm{char}}$, and small momentum transfer, $|t|$ (or $|u|$) ≤ 1 (GeV/c)^2.

Kaidalov has shown that the QGS model describes a large variety of experimental data on the exclusive and inclusive hadronic reactions at high energy very well [5,6,15]. However, due to the duality property of scattering amplitudes [13], this approach can also work in the intermediate-energy region [6]. If in the direct s channel the resonance behavior is essential, the duality property ensures rather good interpolation of the amplitude in average by its Regge asymptotic. Recently, Kaidalov [14] has shown that this approach can describe the reactions $pp \to \pi^+ d$ and $\bar{p}d \to \pi^- p$ [which are also dominated by the three-quark-exchange diagrams similar to one shown in Fig. 1(a)] in the full energy range, starting almost from the threshold. This is clearly shown in Fig. 2 adapted from Ref. [14]: The total cross-section data for the reaction $pp \to \pi^+ d$ [16] are described very well by the Regge model with the exception of the near threshold region. The available data on the reaction $\bar{p}d \to \pi^- p$ (taken near the threshold [17] and calculated at $\sqrt{s} = 3.2$ GeV from the data on the time-reversed reaction $\pi^- p \to \bar{p}d$ [18]) agree also with the Regge model even near the threshold. These results encouraged us to use the quark-gluon model for deuteron photodisintegration starting from $E_\gamma \approx 400$ MeV.

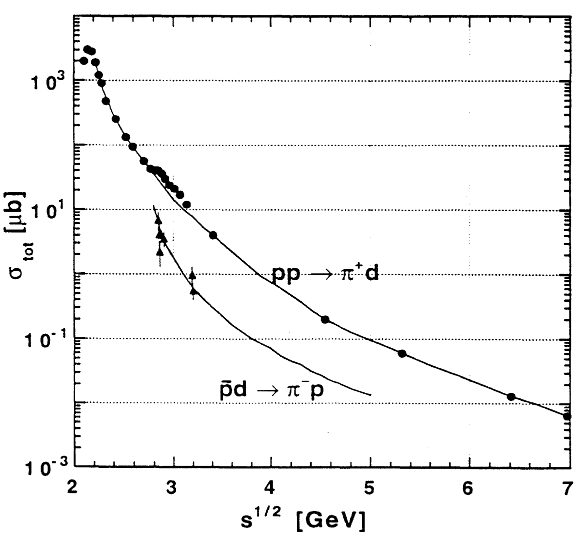

FIG. 2. Total cross sections of the reactions $pp \to \pi^+ d$ [16] and $\bar{p}d \to \pi^- p$, [17,18] as a function of c.m. energy, and the predictions of the QGS model [14].

III. DIFFERENTIAL CROSS SECTION OF THE $\gamma d \to pn$ PROCESS IN THE QUARK-GLUON STRING MODEL

According to the Regge phenomenology and the QGS model, the cross section for the photodisintegration of the deuteron can be parametrized in the form

$$\frac{d\sigma_R}{dt} = \frac{1}{64\pi s} \frac{1}{P_{\mathrm{c.m.}}^2} \left[|T(s,t)|^2 + \frac{1}{R} |T(s,u)|^2 \right], \quad (2)$$

where $P_{\mathrm{c.m.}}$ is the photon momentum in the center-of-mass system, $T(s,t)$ and $T(s,u)$ are the photodisintegration amplitudes, and R is the forward-to-backward ratio of the cross-section values. The energy behavior of $T(s,t)$ for fixed t, which corresponds to the fermion Regge-pole exchange, can be written as [5,6]

$$T(s,t) \approx F(t) \left[\frac{s}{s_0} \right]^{\alpha_N(t)} \exp \left[-i\frac{\pi}{2} \left[\alpha_N(t) - \frac{1}{2} \right] \right], \quad (3)$$

where $\alpha_N(t)$ is the trajectory of the N Regge pole, $F(t)$ is the residue of the pole, s_0 is equal to the square of the deuteron mass, and the factor in the brackets is the phase factor [$T(s,u)$ is given by Eq. (3) substituting t with u]. The baryon Regge trajectory deduced from the data on πN backward scattering is known to have some nonlinearity [15]:

$$\alpha_N(t) = \alpha_N(0) + \alpha_N'(0)t + \tfrac{1}{2}\alpha_N'' t^2, \quad (4)$$

where $\alpha_N'(0) = 0.9$ GeV^{-2}, $\alpha_N'' = 0.25$ GeV^{-4}, and the intercept for the nucleon Regge trajectory N_α (which is relevant to this case) is $\alpha_N(0) = -0.5$. Therefore, the energy behavior of the cross section for the deuteron photodisintegration at small t and high photon energy is predicted to be

$$\frac{d\sigma_R}{dt} \sim \frac{|T(s,t)|^2}{s^2} \sim \left[\frac{s}{s_0} \right]^{2\alpha_N(t) - 2}. \quad (5)$$

The dependence of the residue $F(t)$ on t can be taken from Ref. [14]:

$$F(t) = B \left[\frac{1}{m_N^2 - t} \exp(R_1^2 t) + C \exp(R_2^2 t) \right], \quad (6)$$

where the first term in the square brackets takes into account the nucleon pole in the t channel and the second term is related to the contribution of non-nucleon degrees of freedom in deuteron. In Ref. [14] Kaidalov used Eq. (6), with $B = 9.09$ GeV^2, $R_1^2 = 3$ GeV^{-2}, $R_2^2 = -0.1$

GeV^{-2}, and $C=0.7\ \mathrm{GeV}^{-2}$, to describe the data on the reactions $pp\to\pi^+d$ and $\bar{p}d\to\pi^-p$ in the region $|t|\le 1.6\ (\mathrm{GeV}/c)^2$. Here, we used the same values for the parameters R_2 and C and different values for B and R_1.

In fact, in the deuteron photodisintegration the coupling of photons to the current generated by the quark charges should vanish at the scattering angle $\vartheta=0$, when the transverse motion of quarks is neglected. On the other side, the coupling of photons to the quark magnetic moments does not vanish at $\vartheta=0$. To take into account these two different couplings we assumed $B=(C_1+C_2\sin^2\vartheta)$. The choice of this form of B can also be justified from the phenomenological point of view. Generally speaking, in the framework of Regge approach one has to consider all possible helicity amplitudes which are consistent with gauge invariance, analyticity and conservation of angular momentum (the total number of those amplitudes in the case of the deuteron photodisintegration is equal to 12). Therefore, to have the complete description of the process in the framework of the Regge approach one should parametrize 12 helicity amplitudes. The amplitudes with $(\lambda_1-\lambda_2)\neq(\lambda_3-\lambda_4)$, where λ_1 and λ_2 (λ_3 and λ_4) are the helicities of initial (final) particles, should be equal to zero at $\vartheta=0°$ or 180°. The amplitudes with $(\lambda_1-\lambda_2)=(\lambda_3-\lambda_4)$ do not vanish. This is a consequence of the conservation of the projection of the total angular momentum on the z axis (see, e.g., the formalism developed in Ref. [19]). Being the data on the spin observables for the deuteron photodisintegration scarce, a model-independent parametrization of the 12 helicity amplitudes is not possible. Then, the parametrization $B=(C_1+C_2\sin^2\vartheta)$ corresponds to the differential cross section averaged over the initial and summed over the final helicities. The contributions of the helicity amplitudes which vanish or do not vanish at $\vartheta=0$ are proportional to the terms $C_2\sin^2\vartheta$ or C_1, respectively. The constants C_1 and C_2 were determined from a fit to existing low-energy data at forward and backward angles, as discussed in Sec. IV B. We found $C_1=6.99\ \mu\mathrm{b}^{1/2}\,\mathrm{GeV}^3$ and $C_2=7.12\ \mu\mathrm{b}^{1/2}\,\mathrm{GeV}^3$, which means that the two different couplings are of the same order of magnitude.

As for the R_1 parameter, in the $\gamma d\to pn$ process its value should be smaller than in the reaction $\pi^+d\to pp$ because the coupling of pions to nucleons is not local as compared to photons. In principle, the value of R_1 should also be determined by a fit. However, to decrease the number of parameters of the fit, we chose $R_1^2=1\ \mathrm{GeV}^{-2}$ according to the following considerations: It is known that for a virtual pion the form factor in the πNN vertex can be parametrized as [20]

$$F_{\pi NN}(Q^2)=G_N(Q^2)G_\pi(Q^2)\ ,$$

where $G_N(Q^2)$ and $G_\pi(Q^2)$ are the electromagnetic form factors of the nucleon and the pion. Therefore, the ratio of the πNN and γNN form factors is approximately equal to

$$G_\pi(Q^2)=1/(1+Q^2/m_\rho^2)\ ,$$

which at $Q^2<0.3\ \mathrm{GeV}^2$ can be parametrized as

$$G_\pi(Q^2)\approx\exp(-DQ^2)\ ,$$

with $D\approx 2\ \mathrm{GeV}^{-2}$. Assuming that a similar factorization is valid for the πNN vertex for virtual nucleon,

$$F_{\pi NN}(t)=G_N(t)G_\pi(t)\ ,$$

we found

$$R_1^2(\gamma NN)=R_1^2(\pi NN)-D=1\ \mathrm{GeV}^{-2}\ .$$

In Eq. (2) we have also neglected the interference of the contributions of the protonlike Regge trajectory $T(s,t)$ and of the neutronlike Regge trajectory $T(s,u)$. At sufficiently high energy, $s\gg t_{\mathrm{char}}$, the first contribution produces a forward peak and the second one produces a backward peak, which are very well separated. In this case the interference term is exponentially small and can be neglected. We expect that this interference is numerically small also at intermediate energies. In the angular intervals $\vartheta_{\mathrm{c.m.}}\le 45°$ and $\vartheta_{\mathrm{c.m.}}\ge 135°$, the neutron and proton spectator peaks are well separated in the phase space and the interference is small. Some contribution of the interference might be present at $45°\le\vartheta_{\mathrm{c.m.}}\le 135°$ angles. For the correct estimation of this contribution one should take into account all the helicity amplitudes. As said above, in our case many helicity amplitudes can contribute in the intermediate energy region, and therefore we expect additional cancellations of different interference terms in the differential cross section after averaging over the particle helicities.

As far as the forward-to-backward ratio R for the $\gamma d\to pn$ reaction is concerned, some of us showed that in the naive quark model, it should be related to the charges z_u and z_d of u and d quarks as [4]

$$R=\frac{(d\sigma/d\Omega)_{0°}}{(d\sigma/d\Omega)_{180°}}=\frac{2z_u^2+z_d^2}{2z_d^2+z_u^2}=1.5\ , \qquad (7)$$

while in the QGS model, which takes into account the difference for momentum distributions of u and d quarks in the nucleon, this ratio depends on the energy, increasing from 1.5 at $E_\gamma\sim 0.2$ GeV up to 4 at $E_\gamma\to\infty$. Such a simple value of the ratio R follows from the absence of interference effects which is also consequence of QGS model and Regge phenomenology [5].

IV. COMPARISON TO THE DATA

A. High-energy region

In Figs. 3 and 4 we give the predictions of the differential cross section for the deuteron photodisintegration as a function of the laboratory photon energy in the energy region accessible at CEBAF. The results are given at constant t and constant ϑ, respectively.

As it is seen, the differential cross section is a fast decreasing function of the photon energy and t. In particular, for $t=0$ one has $d\sigma/dt\sim s^{-3}$. At fixed $\vartheta_{\mathrm{c.m.}}$, Eq. (2) predicts a more complex energy behavior:

$$d\sigma/dt\sim F^2(t)s^{(2\alpha-2)}\ ,$$

which generally cannot be incorporated into a simple

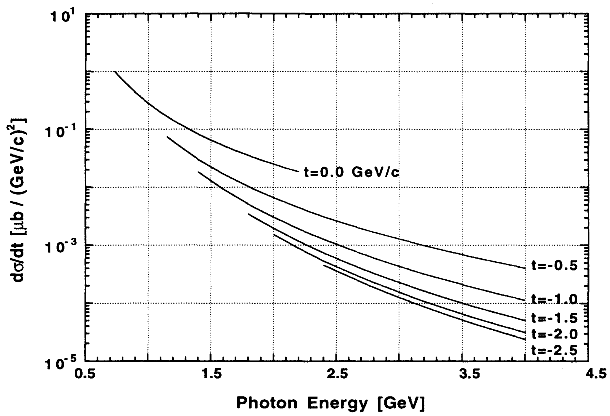

FIG. 3. Differential cross section for deuteron photodisintegration at $t=0$, -0.5, -1, -1.5, -2, and -2.5 $(\mathrm{GeV}/c)^2$ as a function of the photon energy.

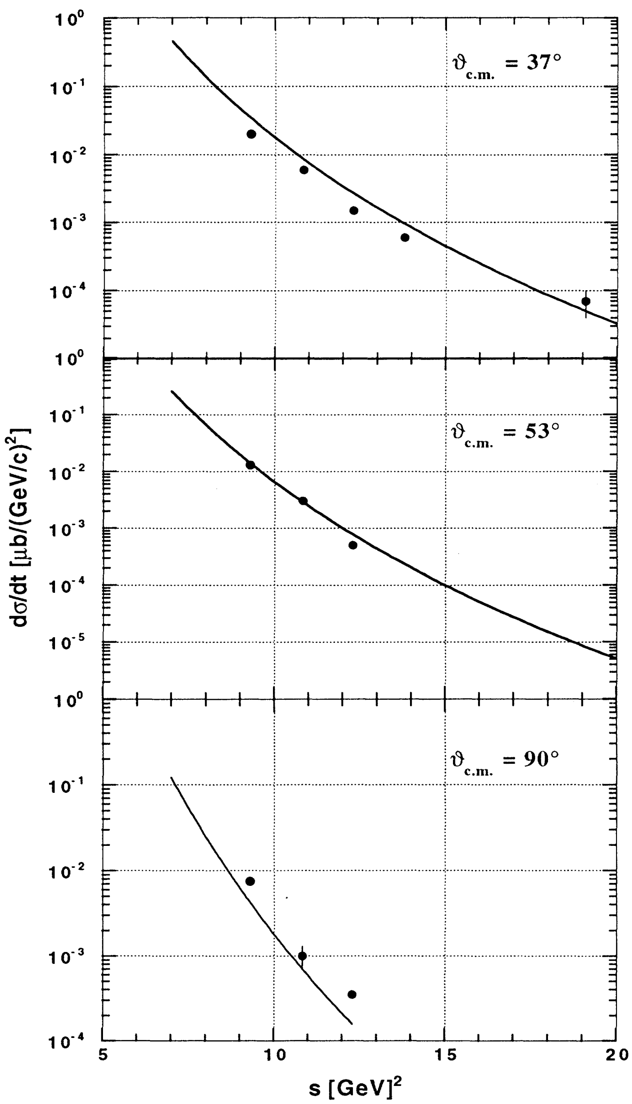

FIG. 4. Differential cross section for deuteron photodisintegration at $\vartheta=37°$, 53°, and 90° as a function of s compared with the data of the NE17 experiment [7].

power law of energy. However, in a limited energy region the parametrization $d\sigma/dt \sim s^{-n}$ can be approximately done, with the power n depending on the angle $\vartheta_{\mathrm{c.m.}}$. In Fig. 4 this parametrization of the differential cross section as a function of s is shown for the given angles: we found different powers at different angles; specifically, $n=5.4$ for $\vartheta_{\mathrm{c.m.}}=0°$, $n=9.1$ for $\vartheta_{\mathrm{c.m.}}=37°$, $n=10.3$ for $\vartheta_{\mathrm{c.m.}}=53°$, and $n=11.8$ for $\vartheta_{\mathrm{c.m.}}=90°$, in distinction from the quark counting rules which predicts $n=11$ at all angles where $t \gg 1$ $(\mathrm{GeV}/c)^2$.

In Fig. 4 we also show the new data obtained by the NE17 experiment at SLAC [7]. That collaboration provided a fit to the data of the form s^{-n} yielding $n=8.7\pm0.3$ for $\vartheta_{\mathrm{c.m}}=37°$, $n=11.0\pm0.5$ for $\vartheta_{\mathrm{c.m.}}=53°$, and $n=12.1\pm0.8$ for $\vartheta_{\mathrm{c.m.}}=90°$, values which are in very good agreement with our predictions. The data at $\vartheta_{\mathrm{c.m.}}=37°$ and 53° are completely in the region of t where our model is valid: at these angles the contribution of the second term of Eq. (2), which is proportional to $1/R$, is negligibly small because $|u|$ is considerably larger than $|t|$. In the evaluation of Eq. (2) at $\vartheta_{\mathrm{c.m.}}=90°$, where $t=u$, we used $R=1.5$, which corresponds to the prediction of the naive quark model [4]. The agreement of the QGS model predictions with the 90° data shows that in the considered energy region the Regge tails are still important at 90°. At higher energies (where $t \sim -s$) the Regge contributions at fixed $\vartheta_{\mathrm{c.m.}}$ should decrease as $s^{-2\alpha'(0)s\ln s}$ and the predictions of quark counting rules will become dominant.

B. Intermediate-energy region: fit to the forward- and backward-angle data

In this section we discuss the fit to the scarce data, available at forward and backward angles and in the energy interval 375–700 MeV, used to determine with low uncertainties the parameters C_1 and C_2.

As we argued at the beginning of Sec. II the QGS model and Regge phenomenology can be applied when the resonancelike structures in the cross section are absent. Therefore, in order to describe these data at low energies we had to take into account the tail of the Δ resonance. We found it inconsistent to add the full contributions of the graphs in Figs. 1(b) and 1(c), because of the problem of the double counting. However, the sharp energy dependence of the photodisintegration amplitude in the Δ-resonance region is largely related to the contribution of the graph in Fig. 1(c). Then, we used the expression

$$\frac{d\sigma}{dt}=\frac{d\sigma_R}{dt}+\frac{d\sigma_\Delta}{dt}\ , \tag{8}$$

where $d\sigma_R/dt$ is the Regge prediction as given by Eq. (2), and $d\sigma_\Delta/dt$ is the Δ-resonance tail contribution. We parametrized this tail according to the graph of Fig. 1(c) calculated in the infinite momentum frame, using the assumptions of the reduced QCD amplitude approach [3], with some weight factor which was used as a free parameter in the fit. We also introduced a cutoff factor which suppresses the contribution of this graph at higher energies. Using Eq. (4) from Ref. [21] we wrote the cross section corresponding to Fig. 1(c) in the following form[1]:

$$\frac{d\sigma_\Delta}{dt}=\frac{1}{64\pi s}\frac{1}{P^2_{\text{c.m.}}}\left[|T^{\text{res}}_\Delta(s,t)|^2+\frac{1}{R_{\text{res}}}|T^{\text{res}}_\Delta(s,u)|^2\right], \tag{9}$$

where

$$|T^{\text{res}}_\Delta(s,t)|^2=4|A^{\text{res}}_{\gamma p\to\pi^0 p}(s_1,t)|^2\mathrm{D}^2(q_1^2)\Delta_d^2 ,$$

$T^{\text{res}}_\Delta(s,u)$ has a similar expression, and the interference between the two contributions is neglected. Here, the factor 4 takes into account the contributions of π^0 and π^- mesons in the intermediate state of Fig. 1(c); the forward-to-backward ratio R_{res} is in this case equal to 1; $A^{\text{res}}_{\gamma p\to\pi^0 p}(s_1,t)$ is the amplitude of the reaction $\gamma p\to\pi^0 p$, averaged over the angular distributions; the function $\mathrm{D}^2(q_1^2)$ takes into account the pion propagator and the form factor in the vertex πNN; and Δ_d is the deuteron structure factor [21] which, in the reduced amplitude approach, has the meaning of the distribution amplitude. The estimates based on the hybrid model of deuteron with the realistic value (0.3–0.7)% of the admixture of six-quark bag in deuteron give $\Delta_d^2=(1.5-2.5\times10^{-5})$ GeV^2 [21]. These values are also in agreement with experimental data on the relative probability of the Pontecorvo reaction $\bar{p}d\to\pi^- p$ at rest, which is about 10^{-5}. Therefore, we took: $\Delta_d^2=2\times10^{-5}$ GeV^2.

The function $\mathrm{D}^2(q_1^2)$ has the form

$$\mathrm{D}^2(q_1^2)=\frac{4m^2f_\pi^2\tilde{\mathbf{q}}_1^2F_\pi^2(q_1^2)}{m_\pi^2(q_1^2-m_\pi^2)^2}, \tag{10}$$

being

$$q_1^2=(p_n-p_d/2)^2 ,$$

$$\tilde{\mathbf{q}}_1^2=4m^2\left[\frac{\mathbf{p}}{E_p+m}-\frac{\frac{\mathbf{p}_d}{2}}{E\left[\frac{\mathbf{P}_d}{2}\right]+m}\right]^2,$$

$$F_\pi^2(q_1^2)=\left[1-\frac{q_1^2-m_\pi^2}{\Lambda^2}\right]^{-2},$$

with $\Lambda^2=1.4$ GeV^2 and $f_\pi^2/4\pi=0.08$.

We parametrized the amplitude $A^{\text{res}}_{\gamma p\to\pi^0 p}(s_1,t)$ in the form

$$|A^{\text{res}}_{\gamma p\to\pi^0 p}(s_1,t)|^2=64\pi^2 s_1(p^1_\gamma/p^1_\pi)_{\text{c.m.}}\delta\sigma_0A(\vartheta)\times\frac{m_\Delta^2\Gamma_{\pi N}\Gamma_\Delta}{(s_1-m_\Delta^2)^2+m_\Delta^2\Gamma_{\pi N}^2}, \tag{11}$$

where

$$\delta=[E_0^2+(E^{\text{res}}_\gamma)^2]/(E_0^2+E_\gamma^2)$$

is a damping factor introduced to suppress the resonance contribution at energies far from the resonance; $A(\vartheta)=(1+b_1\cos^2\theta)/4\pi$; and

$$\Gamma_{\pi N}=\Gamma_\Delta\left[\frac{P^1_\pi}{P^{\text{res}}_\pi}\right]^3\frac{1+(P^{\text{res}}_\pi a)^2}{1+(P^1_\pi a)^2},$$

where $a=0.2$ GeV^{-1}, $P^{\text{res}}_\pi=0.227$ GeV, and $\Gamma_\Delta=0.14$ GeV. The values of the two free parameters $\sigma_0=740$ μb/sr and $b_1=-0.58$ were obtained by a fit.

In Fig. 5 we compare all the experimental data available at (375–700) MeV and at forward and backward angles with the results obtained with Eq. (8). As it is seen, our calculation reproduces the experimental values rather well. For the used set of parameters the contribution of Regge term $d\sigma_R/dt$ is dominant in the whole considered photon energy region: the contribution of $d\sigma_\Delta/dt$ decreases from 30–40% at $E_\gamma=0.4$ GeV to 20–10% at $E_\gamma=0.6$–0.7 GeV.

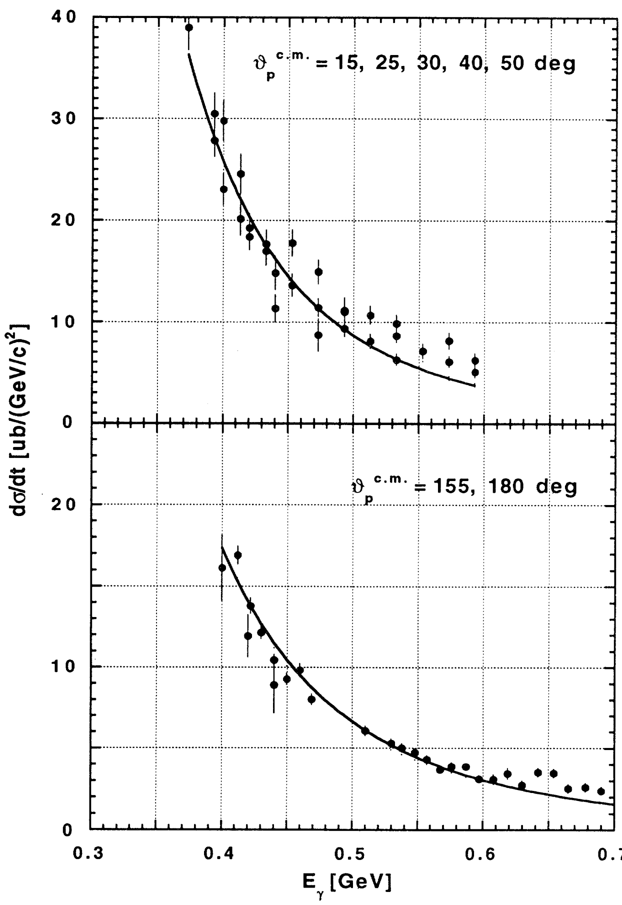

FIG. 5. Comparison of forward and backward data $\gamma d\to pn$ above 375 MeV to our prediction. Data points are from Refs. [8–10].

[1]In what follows we denote with the suffix 1 all variables relevant to the reaction $\gamma N\to\pi N$.

V. CONCLUSIONS

We have derived an expression for the cross section for the $\gamma d \rightarrow pn$ reaction in the framework of the QGS model and Regge phenomenology [Eqs. (2)–(6)]. This expression should work well at sufficiently high energy ($E_\gamma > 1$ GeV) and small t or u [$|t|$ or $|u| \leq 1$ $(\mathrm{GeV}/c)^2$] and might be applied also in the intermediate-energy region ($E_\gamma = 0.5-1$ GeV).

We have compared our predictions to the recent data obtained by the NE17 experiment at SLAC [7] at energies between 1.1 and 4.2 GeV, where our aproach is valid, finding a very good agreement. Moreover, we have also examined the data available at forward and backward angles and at 375–700 MeV [8–10] showing that the process can be well described by our approach at these energies also.

We have not considered spin observables, although one should expect rather important spin effects in this process, as it was observed in the binary reactions $\pi N \rightarrow \pi N$, $\pi N \rightarrow N\rho$ [19,22,23], and in the antiproton-proton annihilation into two pions [24] which are also described by the diagrams with three-quark exchange (or baryon Regge pole) in the t-channel. Therefore, the investigation of the deuteron photodisintegration with polarized photon beam and polarized target should also give important informations on the mechanism of three-quark exchanges and on the spin dependence of the vertex $d \rightarrow N +$Reggeon, which is sensitive to the six-quark component in the deuteron wave function.

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