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DEUTERON PHOTODISINTEGRATION AT INTERMEDIATE ENERGY AND QUARK MODELS

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Abstract: We have examined the behaviour of the forward and backward data for the $\gamma d \to pn$ reaction at intermediate energy in the framework of the quark-gluon model and Regge phenomenology. Our model reproduces rather well the experimental values.

In this paper we examine the data of the reaction $\gamma d \to pn$ available at intermediate energies with the aim of determining whether this process is more economically described in terms of the quark degrees of freedom, rather than nucleon and meson degrees of freedom. In particular, we will try to establish whether the deuteron photodisintegration amplitude obeys to the predictions of the quark-gluon model and Regge phenomenology.

We will first look at the deuteron photodisintegration with the high-energy physicist eye, and then we will try to extrapolate this point of view to the intermediate energy region.

At high energy, it is usefull 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 the region *i*), according to quark-dimensional counting rules, the cross section of the reaction at constant centre-of-mass angle should be a very fast decreasing function of energy:[1]

$$\frac{d\sigma}{dt}(\vartheta_{c.m.} \approx 90°) \sim s^{-11} \,, \tag{1}$$

where s and t are the usual Mandelstam variables. The only data available at high energies, specifically those recently taken at SLAC[2] at $E_\gamma = (0.8\text{-}1.6)$ GeV (see Fig. 1), suggest this behaviour according to the simple constituent-counting rule, but this is not a conclusive proof that quarks are needed in an explanation. First, the data cover a limited energy and angular region, corresponding to $|t| = 1 \div 2.(GeV/c)^2$. Second, conventional nuclear theories can scale as s^{-11}.

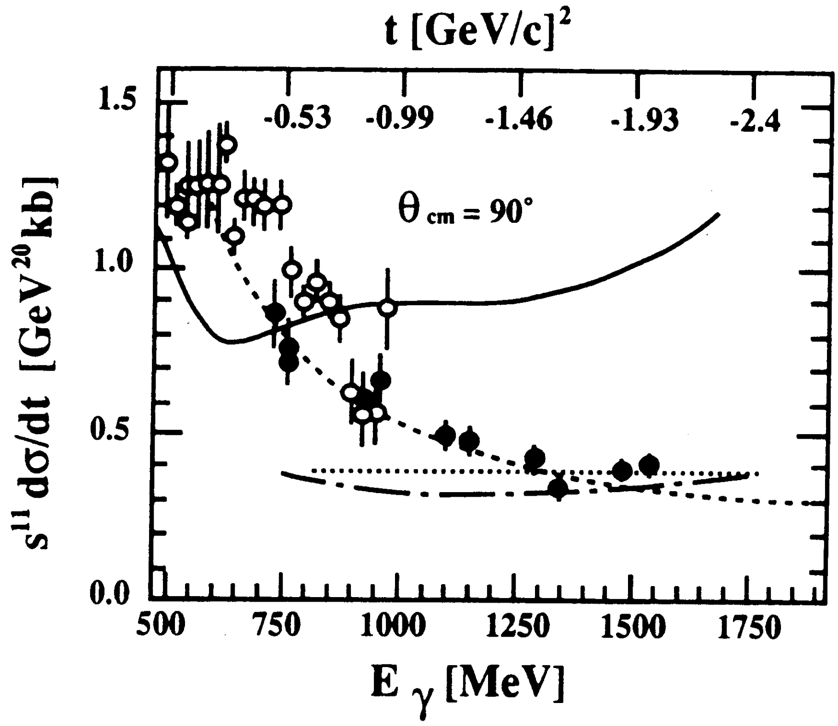

FIG. 1 - Comparison of high energy $\gamma d \rightarrow pn$ data at 90° to quark model predictions: solid circles Ref. [2], open circles Ref. [3]. The dotted line indicates an energy dependence of s^{-11}; the dashed curve indicates the dependence predicted by the factorization model of Brodsky and Hiller;[1] the solid curve is the prediction of a meson-nucleon model; the dot-dashed curve is our prediction [Eq. (8)] (adapted from Ref. [2]).

In the region *ii*), that is at sufficiently high energy and small *t* or *u*, the photodisintegration amplitude is dominated by the exchange of 3 valence quarks in *t*- or *u*-channel (see Fig. 2a) with any number of gluons exchanged between them. In the framework of $1/N_c$ expansion in QCD, this is the consequence of the dominance of the planar-quark-gluon graph. This expansion was first considered by t'Hooft[4] who proposed to analyze the properties of non-abelian quantum field theory in the large N_c limit. Then, the behaviour of different quark-gluon graphs according to their topology was discussed by Rossi and Veneziano.[5] To describe different binary reactions at high energy, Kaidalov[6] has proposed the so-called quark-gluon-model (QGM). This model is based on the propeties of $1/N_f$ expansion in QCD and can be considered as a microscopic model for Regge phenomenolgy, which, in its turn, is based on fundamental properties of scattering amplitudes such as analiticity, unitarity and crossing-symmetry.

In the Regge language the dominant contribution of 3-quark-exchange correponds to the fermion Regge pole [see in Fig. 2b where the wavy line describes the exchange of a Reggeon, which is an assembly of 3 quarks plus many gluons with angular momentum $\alpha(t)$]. The analysis of binary hadronic reactions[5-6] shows that this picture works very well at high energies and $|t|$ or $|u| \leq 1(GeV/c)^2$. However, due to the duality property of scattering amplitudes,[5] this approach can work also in the intermediate energy region.[7] If in the direct *s* channel the resonance behaviour is essential, the duality property ensures rather good interpolation of the amplitude in average by its Regge asymptotics. In Ref. [9] it has been shown that this approach can describe the reactions $pp \to \pi^+ d$ and $\bar{p}d \to \pi^- p$ in the full energy range, starting almost from the threshold.

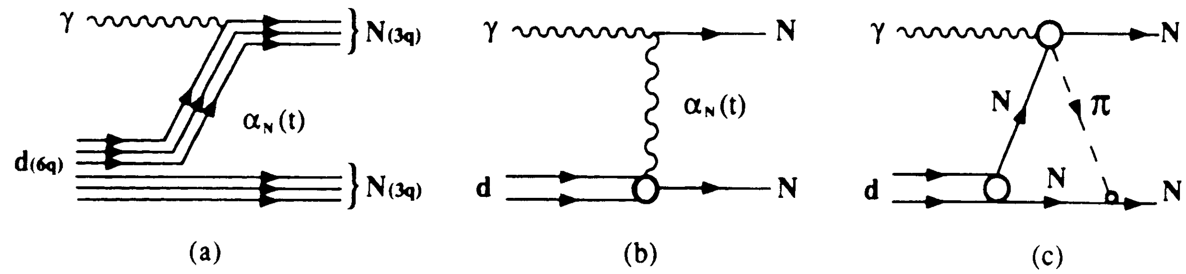

FIG. 2

Let us note that at large energies the diagram of Fig. 2b includes the contribution of the graph of Fig. 2c. The amplitude $\gamma N \to \pi N$ in Fig. 2c can be described by the Regge pole exchange and the triangle can be included into the vertex d→N+Reggeon. This statement can be valid at sufficiently high energy and small t. In the resonance region, $E_\gamma \leq 1$ GeV, when the local correspondance between the Regge and resonance amplitude is absent, the contribution of the diagram in Fig. 2c can not be incorporated completely into the amplitude corresponding to the diagram in Fig. 2b. This statement is also not true for large t when the amplitude $\gamma N \to \pi N$ can not be described by the Regge exchange. The vertex d→N+Reggeon can not be described only by nucleon degrees of freedom in deuteron and contains essential contributions from non-nucleonic components and, in particular, from 6-quark bag admixture in the deuteron wave function.[9]

Let us parametrize the cross section in the form:

$$\frac{d\sigma_R}{dt} = \frac{1}{64\pi s}\,\frac{1}{P^2_{c.m.}}\left(|T(s,t)|^2 + \frac{1}{R}\,|T(s,u)|^2\right), \tag{2}$$

where $P_{c.m.}$ is the photon momentum in the centre-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 use of Eq. (2) can be justified for $|t| \leq 1$ $(GeV/c)^2$ when the first term is dominant or for $|u| \leq 1$ $(GeV/c)^2$ when the second term is dominant. The energy behaviour of T(s,t) for fixed t, which corresponds to the fermion Regge pole exchange, can be written as:[7]

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

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, m_d^2, 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 non linearity:[8]

$$\alpha(t) = \alpha(0) + \alpha'(0)\,t + \frac{1}{2}\alpha'' t^2\ , \tag{4}$$

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

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

which is much more flat dependent on s as compared with the region *i*) of large $|t|$ or $|u| \sim s \gg m^2$. In particular, for example, at $t=0$, one has: $d\sigma_R/dt \sim s^{-3}$.

The dependence of the residue $F(t)$ on t can be taken from ref. [9]:

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

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.[9] Eq. (6), with $B = 9.09$ GeV^2, $R_1^2 = 3$ GeV^{-2}, $R_2^2 = -0.1$ GeV^{-2}, and $C = 0.7$ GeV^{-2}, was used to describe data on the reactions $pp \to \pi^+ d$ and $\bar{p}d \to \pi^- p$. In our case, the coupling of photons to the current generated by the quark charges should vanish at scattering angle $\vartheta=0$, when the transverse motion of quarks is neglected. To take into account the relative suppression of this coupling at $\vartheta=0$ as compared with the γ coupling to the quark magnetic moments we assumed $B=(C_1 + C_2 \sin^2\vartheta)$. Moreover, we took a different value for the parameter R_1: the coupling of pions to nucleons is not local as compared to photons, then we expected that in our case R_1^2 should be smaller than in the reaction $\pi^+ d \to pp$. We chose $R_1^2 = 1$ GeV^{-2}.

The forward-to-backward ratio R was discussed using this approach in ref.[10]. In the naive quark-model, this ratio should be related to the charges of u- and d-quarks as:

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

while in the quark gluon string model, which takes into account the difference for distributions of u-and d-quarks in nucleon, this ratio should increase from 1.5 at $E_\gamma \sim 0.2$ GeV up to 4 at $E_\gamma \to \infty$.

Strictly speaking Eq. (2) should be used at sufficiently high energies, say $E_\gamma > 1$ GeV; nevertheless, as it was said above, this approach might be valid already at lower energy, provided that the Δ-resonance tail contribution is taken into account. Then, we tried to reproduce the scarse data available at energy $E_\gamma \geq 400$ MeV by the expression :

$$\frac{d\sigma}{dt} = \frac{d\sigma_R}{dt} + \frac{d\sigma_\Delta}{dt} , \qquad (8)$$

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. 2c calculated in the infinite momentum frame, using the assumptions of the reduced QCD amplitude approach.[1] Using eq. (4) from ref. [11] we wrote the cross-section corresponding to Fig. 2c in the following form:*

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

where: $|T^{res}_\Delta(s,t)|^2 = 4\,|A^{res}_{\gamma p\to\pi^0 p}(s_1,t)|^2\,D^2(q_1^2)\,\Delta_d^2$, $T^{res}_\Delta(s,u)$ 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. 2c; the forward-to-backward ratio R_{res} is in this case equal to 1; $A^{res}_{\gamma p\to\pi^0 p}(s_1,t)$ is the amplitude of the reaction $\gamma p\to\pi^0 p$, averaged over the angular distributions; the function $D^2(q_1^2)$ takes into account the pion propagator and the form factor in the vertex πNN; and Δ_d is the deuteron structure factor[11] which, in the reduced amplitude approach, has the meaning of the distribution amplitude.

The estimates based on the hybrid model of deuteron with a realistic value[11] [(0.3÷0.7)%] of the admixture of 6q-bag in deuteron give $\Delta_d^2 = (1.5\div 2.5)\cdot 10^{-5}\,GeV^2$. These values are also in agreement with experimental data on the probability of the Pontecorvo reaction $\bar{p}d\to\pi^- p$ at rest. Therefore, we took: $\Delta_d^2 = 2\cdot 10^{-5}\,GeV^2$.

The function $D^2(q_1^2)$ has the form:

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

being:

$$q_1^2 = (p_n - \frac{p_d}{2})^2;\quad \tilde{q}_1^2 = 4m^2\left[\frac{p}{E_p+m} - \frac{\frac{p_d}{2}}{E(\frac{p_d}{2})+m}\right]^2;\quad F_\pi^2(q_1^2) = \left[1 - \frac{q_1^2 - m_\pi^2}{\Lambda^2}\right]^{-2};\ \text{with } \Lambda^2 = 1.4\,GeV^2$$

and $f_\pi^2/4\pi = 0.08$.

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

$$|A^{res}_{\gamma p\to\pi^0 p}(s_1,t)|^2 = 64\pi^2 s_1\left(\frac{p^1_\gamma}{p^1_\pi}\right)_{c.m.} C_3\,\delta\,\sigma_0\,A(\vartheta)\,\frac{m_\Delta^2\Gamma_{\pi N}\Gamma_\Delta}{(s_1 - m_\Delta^2)^2 + m_\Delta^2\Gamma_{\pi N}^2} \tag{11}$$

where $\sigma_0 = 380\ \mu b/sr$; δ is a damping factor introduced to suppress the resonance contribution at high energies, far from the resonance:

$$\delta = \frac{E_0^2 + \left[E_\gamma^{res}\right]^2}{E_0^2 + E_\gamma^2};\quad A(\vartheta) = \frac{1 + b_1\cos^2\vartheta}{4\pi};\quad \text{and } \Gamma_{\pi N} = \Gamma_\Delta\left(\frac{P^1_\pi}{P^{res}_\pi}\right)^3 \frac{1 + (P^{res}_\pi a)^2}{1 + (P^1_\pi a)^2};$$

C_3 and b_1 are free parameters, $a = 0.2\ GeV^{-1}$, $P^{res}_\pi = 0.227\ GeV$, and $\Gamma_\Delta = 0.14\ GeV$. In distinction from Eq. (2), the formula (9) can be used also for large angles.

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

In Fig. 3 we compare all the experimental data available at $E_\gamma \geq 0.35$ GeV and at forward and backward angles with the results obtained with Eq. (8) for the following values of parameters: $C_1 = 8.4\ \mu b^{1/2}GeV^3$, $C_2 = 7.98\ \mu b^{1/2}GeV^3$, $C_3 = 0.8$, $b_1 = -0.3$, $R = 1.5$. As it is seen, our calculation reproduces rather well the experimental values. For the used set of parameters the contribution of Regge term $d\sigma_R/dt$ is dominant in the whole considered photon energy region. Nevertheless at $E_\gamma = 0.4$ GeV the contribution of $d\sigma_\Delta/dt$ is not very small and reaches 30-40%.

As it was mentioned before, we expect that our approach is valid at high energy and $|t| \leq 1$ (GeV/c)^2 or $|u| \leq 1$ (GeV/c)^2. Nevertheless, we compared our model, without adjusting any parameter, also with the SLAC data[2] at $\vartheta_{c.m.} = 90°$, which correspond to $|t| = 1\div2$ (GeV/c)^2. As it is seen in Fig. 1 (dot-dashed curve), we found a reasonable agreement between our prediction and the data at $E_\gamma \geq 1.25$ GeV. Moreover, it is worth mentioning that our model gives also a very flat prediction for $s^{11}d\sigma/dt$ at $E_\gamma = (0.7\div1.75)$ GeV. This suggests that the Regge tails can give important contributions at all angles when the energy is not very high. Of course, while the energy increases, the Reggeon contributions at $\vartheta_{c.m.}$ = const decreases exponentially like $exp\ (-2\alpha'(0)\ s\ lns)$.

In conclusion, it is clear the need of good data on the deuteron photodisintegration in broader energy and angular intervals in order to determine which model describe better the mechanism of the process.

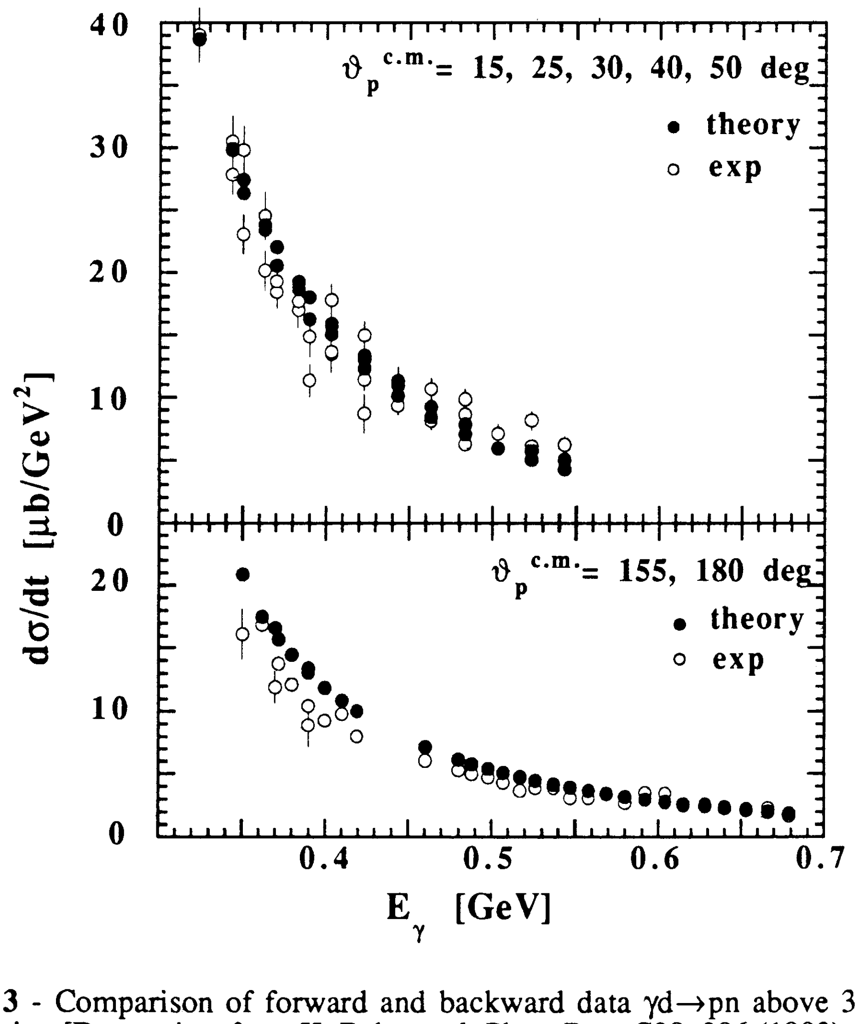

FIG. 3 - Comparison of forward and backward data $\gamma d \to pn$ above 350 MeV to our prediction [Data points from K. Baba et al. Phys. Rev. C28, 286 (1983); J. Arends et al., Nucl. Phys. A412, 509 (1984); K.H. Althoff et al., Z. Phys. C21, 149 (1983)].

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