Meson-Exchange Calculation of the $d(\gamma,p)n$ Reaction in the GeV Energy Region DE91 017994

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ABSTRACT

We show that a meson-exchange model of the $d(\gamma,p)$ reaction can be constructed to reproduce the energy-dependence of the existing data for the differential cross section at 90° . The prediction of the model in the GeV energy region is found to be radically different from the QCD prediction by Brodsky and Hiller.⁶ The results will be compared with the new data presented in a companion paper.

With the assumption that nuclear phenomena can be effectively described in terms of hadronic degrees of freedom, the mechanism of the $d(\gamma,p)n$ reaction can be considered to consist of two parts: (1) the incident photon is absorbed by one of the nucleons in the deuteron and pions or heavier mesons are produced and subsequently absorbed by the second nucleon, (2) the two outgoing nucleons interact with each other through the exchange of mesons. This somewhat conventional approach has been fairly successful in describing the main features of the data in the low energy region,¹ and has been extended²⁻⁴ to the intermediate energy region with reasonable results.

With the development of quantum chromodynamics (QCD) as the theory of strong interactions, an interesting and important question to ask is: at what energy does the meson-exchange model outlined above breakdown and the quark-gluon degrees of freedom become significant? It is of course very difficult, if not impossible, at the present time to answer this question theoretically. The

alternative is to calculate the energy-dependence of various reaction cross sections from a meson-exchange model and compare them with the experimental data in the high-energy region where the need for a QCD treatment has been suggested. With the recent measurements⁵ which extend the differential cross section data for the $d(\gamma, p)n$ reaction at several angles up to about 2 GeV, we indeed now can carry out such a study concerning the the QCD prediction of Brodsky and Hiller.⁶ The objective of this paper is to facilitate this study by providing the needed predictions from a meson-exchange model. Our predictions will be compared with the new data reported in the companion paper by Napolitano et al.⁵

The meson exchange model of the $d(\gamma, p)n$ reaction considered in this work is illustrated in Fig. 1. The exchanged particle can be a pion or a heavier meson. The kinematics are given in the center of mass frame. To carry out the theoretical calculation, we need a model for generating the off-shell amplitude F of the $\gamma + N \rightarrow N + \text{Mesons}$ process and a model for describing the absorption of the produced mesons and the half-off-shell t matrix of the subsequent NN interaction (Fig. 1b). We start with the coupled channel meson-exchange model of NN scattering developed in Ref. 7. It is obtained by extending the Paris potential⁸ to include the coupling to the Λ and the $N^*(1470)$ Roper resonance. The associated one-pion and two-pion production mechanisms are described by the standard isobar model with the vertices $\Lambda \rightarrow \pi N$, $N^* \rightarrow \pi N$ and $N^* \rightarrow \pi \Lambda$. The model proves⁷ to be reasonable in describing the NN phase shifts as well as various NN total cross sections up to 2 GeV, and is therefore suitable for generating the half-off-shell NN t -matrix shown in Fig. 1b. In this way the energy-dependence originating from the final NN interaction is constrained in our calculation by the NN data.

Our next task is to construct a model for generating the photo-meson amplitude F . It has been fairly well established²⁻⁴ that the main features of the

γN reaction up to about a few hundred Mev can be described by a Born term deduced from a field-theoretical Lagrangian and a resonant term describing the excitation of the Δ . For simplicity, we take the Born term from Ref. 2. In an approach consistent with the NN model of Ref. 7 and the existing more sophisticated πNN theories,⁹ an isobar model for $\gamma N \rightarrow \Delta \rightarrow \pi N$ has been constructed in Ref. 4. For the present study we need to extend the model to also include the $\gamma N \rightarrow N^* \rightarrow \pi N$ and $\gamma N \rightarrow N^* \rightarrow \pi \Delta \rightarrow \pi \pi N$ amplitudes. To simplify the subsequent γd calculation we approximate the two-pion channel by $\gamma N \rightarrow N^* \rightarrow \sigma N$, where σ is a fictitious scalar-isoscalar particle. This approximation of the 2π continuum is commonly used in meson-exchange models of nuclear force. Its justification, of course, depends on whether an acceptable fit to the γN data can be achieved. With this simplification, the resonant part of the γN amplitude F takes the following form (suppress isospin indices)

$$\begin{aligned}
 \langle \vec{q} \lambda \vec{p}' | F(E) | \vec{p} \vec{k} \rangle = & \frac{g_{\gamma N, \Delta}}{(2\pi)^3 M_\Delta} \frac{i(\vec{\epsilon}_\lambda \cdot \vec{L} \times \vec{q})}{E - M_\Delta + i\Gamma_\Delta(\kappa, \kappa_\Delta)} f_{\Delta, \pi N}(\vec{k}) \frac{1}{\mu} (\vec{L} \cdot \vec{k}) \\
 & + \frac{g_{\gamma N, N^*}}{(2\pi)^3 M_{N^*}} \frac{\vec{\epsilon}_\lambda \cdot (\vec{p}' + i(\vec{\sigma} \times \vec{q}))}{E - M_{N^*} + i\Gamma_{N^*}(\kappa, \kappa_{N^*})} \\
 & \times \left[\frac{1}{\mu} (\vec{\sigma} \cdot \vec{k}) f_{N^*, \pi N}(\kappa) + f_{N^*, \sigma N}(\kappa) \right] \quad (1a)
 \end{aligned}$$

where $M_\Delta = 1236$ MeV, $M_{N^*} = 1470$ MeV, $\vec{\epsilon}_\lambda$ is the photon polarization vector, $\vec{\sigma}$ is the Pauli spin operator, $\vec{L}$ is the transition spin operator for the $N \rightarrow \Delta$ transition. E is the total energy. $\vec{k}$ is the relative momentum of the πN or σN subsystem. The form factors and the widths Γ_Δ and Γ_{N^*} are defined by ($a = \Delta, N^*$, $\beta = \pi, \sigma$)

$$f_{a,\rho N}(\kappa) = \frac{f_{a,\rho N}^0}{(2\pi)^{3/2}} \frac{1}{\sqrt{2E_\rho(\kappa)}} \left[\frac{\Lambda_{a,\rho N}^2}{\Lambda_{a,\rho N}^2 + \kappa^2} \right] \quad (1b)$$

$$\Gamma_a(\kappa, \kappa_a) = \frac{1}{2} \left(\Gamma_a^0 \right) \left[\frac{\Lambda_{a,\pi N}^2 + \kappa_a^2}{\Lambda_{a,\pi N}^2} \right]^2 \left[\frac{M_a E_\pi(\kappa_a)}{W(\kappa) E_\pi(\kappa)} \right] \left[\frac{\kappa}{\kappa_a} \right]^3. \quad (1c)$$

where $E_\rho(\kappa) = \sqrt{\kappa^2 + M_\rho^2}$ for the particle ρ with a mass M_ρ , $W(\kappa) = E_\pi(\kappa) + E_N(\kappa)$, $\Gamma_a^0 = 110, 220$ MeV and $\kappa_a = 228, 416$ MeV/c for $a = \Delta, N^*$.

The Born term and the parameters for the Δ excitation, $g_{\gamma N, \Delta} = 3.6$, $f_{\Delta, \pi N}^0 = 6.01$, and $\Lambda_{\Delta, \pi N} = 358$ MeV/c are taken from the work of Ref. 4. The parameters $f_{N^*, \pi N}^0 = 0.32$, and $\Lambda_{N^*, \pi N} = 600$ MeV have been deduced from the model in Ref. 7. The mass of the σ particle is assumed to be 500 MeV. We adjust the parameters of the vertex functions $\gamma N \leftrightarrow N^*$ and $N^* \leftrightarrow \sigma N$ to fit the γN total cross section data up to 2 GeV. With the parameters $g_{\gamma N, N^*} = 2.0$, $f_{N^*, \sigma N}^0 = 5.0$, and $\Lambda_{N^*, \sigma N} = 1000$ MeV/c, we obtain the fit (solid curve) shown in Fig. 2. The dashed curve is obtained by keeping only the Born term and the Δ -excitation term. Clearly the excitation of the N^* is essential for describing the data in the GeV energy region. The remaining discrepancies with the data, especially in the energy region near 1000 MeV, can be reduced by including the excitation of higher nucleon resonances. For the present study, the fit is sufficient for justifying the use of the model.

The last dynamical input to our calculation are the πNN and σNN vertices for describing the absorption of π and σ by the second nucleon. They are taken to be of the following form ($\beta = \pi, \sigma$)

$$F_{\beta NN}(\kappa) = \frac{f_{\beta NN}}{(2\pi)^{3/2}} \frac{1}{\sqrt{2E_\beta(\kappa)}} \left[\frac{\Lambda_{\beta NN}^2}{\Lambda_{\beta NN}^2 + \kappa^2} \right] O_\beta, \quad (2)$$

where $O_\beta = \hat{\sigma} \cdot \hat{k} / \mu$, 1 for $\beta = \pi, \sigma$. With the known value $f_{\pi NN} = 1$ our task is to adjust the parameters $A_{\pi NN}$, $A_{\sigma NN}$ and the coupling constant $f_{\sigma NN}$ to fit the $d(\gamma, p)n$ data at 90° in the energy region below 1 GeV, and then to predict the energy-dependence in the higher energy region where the new measurements have been performed.

The quantity of interest is the square of the reduced amplitude $|f|^2$ defined by Brodsky and Hiller.⁶ In terms of the c.m. kinematics (Fig. 1), it is defined by

$$|f|^2 \sim \left(\frac{d\sigma}{d\Omega} \right)_{\text{c.m.}} P_T^2 \left[s(s - m_d^2) \right]^{1/2} F_N^{-2}(\hat{t}_n) F_p^{-2}(\hat{t}_p) \quad (3)$$

where $s = (q + E_d(-\vec{q}))^2 = (2E_N(\vec{p}))^2$, $\hat{t}_p = (E_N(\vec{p}) - \frac{1}{2} E_d(-\vec{q}))^2 - (\vec{p} + \frac{1}{2} \vec{q})^2$,

$\hat{t}_n = (E_N(\vec{p}) - \frac{1}{2} E_d(-\vec{q}))^2 - (-\vec{p} + \frac{1}{2} \vec{q})^2$, and $P_T^2 = (s - m_d^2) \sin^2 \theta_{\text{c.m.}} / 4$.

The nucleon form factor is given by $F_N(\hat{t}) \sim 1/(1 - \hat{t}/0.71 \text{ GeV}^2)^2$. With $A_{\pi NN} = 650 \text{ MeV}/c$, $A_{\sigma NN} = 700 \text{ MeV}$, and $f_{\sigma NN} = 1.2$, our fit to the existing differential cross section data at 90° is shown in Fig. 3. The discrepancies in the energy region from 500 to 1000 MeV are perhaps mainly due to our " σ "-approximation of the 2π continuum and the neglect of higher nucleon resonances. However, the model does reproduce the slope of the existing data. In a schematic QCD calculation, Brodsky and Hiller⁶ predicted that $|f|^2$ approaches a constant as the incident photon energy exceeds only about 1 GeV. Clearly, it (the dashed curve in Fig. 3b) is radically different from the prediction of the meson-exchange model employed here.

It is necessary to analyze the dynamical origins of our prediction and to examine the extent to which our prediction is model independent. We have carried out such a study similar to what has been done in Ref. 9 for the πNN interactions. Our results cannot be reported here because of its length, but will

be published elsewhere. Instead, we will illustrate our findings with a schematic model which can be explicitly presented here and nevertheless reveals the main dynamical content of our calculation in the GeV energy region. In the schematic model all of the spin-isospin complications are suppressed and the photon-meson amplitude F is described by a process $\gamma N \rightarrow R \rightarrow MN$, where R is a "resonance" and M is the produced "meson". The simplified amplitude F takes the form of the A term in Eq. (1a), but with the simplification that $\vec{\epsilon}_\lambda \cdot (\vec{L} \times \vec{q})(\vec{L} \cdot \vec{k}) \rightarrow qk$, $M_R \rightarrow M_R$ and $\Gamma_R \rightarrow \Gamma_R = \text{constant}$. Within our coupled-channel formulation^{7,9} of the problem, the differential cross section of the $d(\gamma, p)n$ reaction for the schematic model can then be written explicitly as (see the kinematics shown in Fig. 1)

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{c.m.}} \sim \frac{(2\pi)^2}{(E_d(q)+q)} \frac{E_d(q)}{q} \frac{E_N(p)p}{2} |T_0(\vec{q}, \vec{p}) + T_1(\vec{q}, \vec{p})|^2 \quad (4a)$$

where

$$T_0(\vec{q}, \vec{p}) = \int d\vec{p}' \phi_d(\vec{p}') \left[\frac{E_{\gamma N, R}}{M_R} q \right] \frac{1}{E - E_N(-\vec{p}' - \frac{\vec{q}}{2}) - E_R(\vec{p}' + \frac{\vec{q}}{2}) + i\Gamma_R} \left[\frac{1}{m_M} \right]^2 \\ \times \left[\frac{A_{R, MN}^2}{A_{R, MN}^2 + k^2} \frac{k}{\sqrt{E_M(k)}} \right] \frac{1}{E - E_N(-\vec{p}' - \frac{\vec{q}}{2}) - E_N(\vec{p}) - E_M(\vec{k}) + i\epsilon} \left[\frac{A_{MNN}^2}{A_{MNN}^2 + k'^2} \frac{k'}{\sqrt{E_M(k')}} \right], \quad (4b)$$

$$T_1(\vec{q}, \vec{p}) = \int d\vec{p}' T_0(\vec{q}, \vec{p}') \frac{1}{E - 2E_N(\vec{p}') + i\epsilon} t(\vec{p}', \vec{p}, E) \quad (4c)$$

where $E_R(p) = \sqrt{M_R^2 + p^2}$, $E_M(k) = \sqrt{k^2 + m_M^2}$, and $E_N(p) = \sqrt{m^2 + p^2}$ are respectively the energy of the "resonance", the exchanged "meson" and the nucleon. E is the total energy and $\vec{k} = \vec{q}/2 + \vec{p}' - \vec{p}$. $\vec{k}(\vec{k}')$ is the meson-nucleon relative momentum calculated from the momenta $\vec{k}$ and $\vec{p}$ ($\vec{k}$ and $-\vec{p}' - \vec{q}/2$). $\phi_d(\vec{p}')$ is the s -wave part of the deuteron wave function. With $M_R = 1300$ MeV, $\Gamma_R = 200$ MeV, $A_{R, MN} = A_{MNN} = 800$ MeV/c, and $m_M = 140$ MeV, we find that the schematic model

defined by Eq. (4) can reproduce the energy-dependence of our calculation in the $E \geq 500$ MeV high energy region. The calculated $|f|^2$ is the solid curve in Fig. 4.

It is seen from Eq. (4) that the energy-dependence of the considered meson-exchange model is mainly characterized by the propagators of the intermediate states. The half-off-shell NN t matrix $t(p', p, E)$ and form factors at the vertices $R \rightarrow MN$ and $MN \rightarrow N$ also contain energy-dependences (since $\vec{k} = \vec{q}^*/2 + \vec{p}' - \vec{p}$ in Fig. 1) which are not so explicit. The deuteron wave function of course plays an important role since it dictates the relative importance between amplitudes with different initial nucleon momenta. We now illustrate in more detail the extent to which our prediction of $|f|^2$ depends on these dynamical factors.

We first show in Fig. 4a that the final state interaction plays a significant role in generating the rising slope of $|f|^2$. When the final state interaction (FSI) term T_1 in Eq. (4a) is set to zero, the calculated $|f|^2$ differs significantly from the full calculation. Since our NN t -matrix is constrained by the NN data, we believe that the effect shown in Fig. 4a should also be present in any meson-exchange calculation.

The most sensitive dynamical quantities in our calculation are the ranges $\Lambda_{R,MN}$ and Λ_{MNN} of the meson-baryon-baryon form factors. In Fig. 4b we show that the slope of $|f|^2$ starts to decrease at $E > 1500$ MeV if $\Lambda_{R,MN} = \Lambda_{MNN} = 500$ MeV/c is used. Of course, a very small value of the range of the form factor is meaningless in a meson-exchange model. But even with this freedom, we are not able to get a constant $|f|^2$ in the 1 to 2 GeV energy region, as predicted by Brodsky and Hiller.⁶

Recall that in our full calculation we use a fictitious σ particle to approximate the two-pion continuum. It is, therefore, necessary to investigate

the extent to which our prediction depends on this "one-boson-exchange" simplification. In Fig. 4c we compare three recent calculations using $m_M=140, 500, 760$ MeV to evaluate the meson energy E_M in Eq. (4b). It is seen that the slope of $|f|^2$ increases as the mass of the exchanged meson increases. This implies that even if we extend the model to include the exchange of heavier mesons, such as ρ and ω , the resulting energy-dependence will not be a constant unless there is a very accidental cancellation. We indeed have explored this possibility, but have not been able to obtain such a model with the freedom we have.

In Fig. 4d, we demonstrate the sensitivity of our prediction to the choice of the deuteron wave function. It is seen that the difference between the predictions from the Paris⁸ and Argonne-v14¹⁰ deuteron wave functions are significant. However, both models yield rising slopes. We have also considered other wave functions. None of them can give a constant $|f|^2$ in the 1 to 2 GeV energy region.

In summary, we have presented a meson-exchange calculation of the $d(\gamma, p)n$ reaction at 90° in the GeV energy region. The parameters of the considered meson-exchange model, illustrated in Fig. 1, are constrained by the data of the elementary γN and NN reactions, and also by the $d(\gamma, p)n$ data below 1 GeV. The predicted energy-dependence of the square of the reduced amplitude $|f|^2$ differs significantly from the QCD prediction by Brodsky and Hiller.⁶ By investigating the dynamical origins of our prediction, we conclude that a constant $|f|^2$ in the 1 to 2 GeV energy region cannot be obtained within a coupled-channel formulation^{7,9} of the meson-exchange model.

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FIGURE CAPTIONS

- Fig. 1 Kinematics of the considered meson-exchange model of the $d(\gamma,p)n$ reaction in the c.m. frame.
- Fig. 2 The calculated γp total cross section (solid curve) is compared with the experimental data.¹¹ The dashed curve is the result with the N^* term of Eq. (1a) neglected.
- Fig. 3 The calculated differential cross section and $|f|^2$ at 90° of the $d(\gamma,p)n$ reaction are compared with the data.¹² The dashed line represents schematically the QCD prediction by Brodsky and Hiller.⁶
- Fig. 4 Comparison of various $|f|^2$ calculated from the schematic model defined by Eq. (4). See the text for the meaning of each curve. In each case, all curves are normalized to the value of the solid curve at 500 MeV.

(a)

(b)

Fig. 1

Fig. 2

Fig. 3

Fig. 4