Comparison of meson-exchange and QCD calculations of $\gamma d \rightarrow np$ reaction

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Abstract

We report a calculation of $\gamma d \rightarrow np$ reaction up to GeV energy region, based on a meson-exchange theory developed in the study of intermediate energy NN and πd reactions. The result is in a sharp disagreement with a QCD prediction by Brodsky and Hiller.

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A new development in nuclear study is to investigate the quark degrees of freedom in nuclei. The research in this direction must confront the fact that the conventional meson theory of nuclear force works to a very large extent. Both approaches start with definite theoretical assumptions, but unfortunately neither one of them can give meaningful predictions unless certain phenomenological procedures have been employed. In the conventional approach, the phenomenology is in the parameterization of short-range interactions in terms of meson-baryon-baryon form factors or some convenient functions of the relative coordinate and momentum. This approach has a long history and has been recently extended¹⁻⁴ to describe NN collision in GeV energy regions. The approach⁵⁻⁶ based on quark dynamics is still in a developing stage. Although many strong claims have been made, only very limited NN calculations have been carried out.

In this paper, we shall make use of a well-tested π NN theory¹⁻³ to address a very specific question raised by a QCD prediction of photo-disintegration of the deuteron in the GeV energy region. The work of Brodsky and Hiller⁵ claimed that even at relatively low photon energy $E_\gamma \gtrsim 1$ GeV the quark dynamics already dominant and one must give up the conventional approach entirely. In this paper we present results calculated from the meson-exchange model developed in Refs. 1-3 in order to set a scale for assessing this strong claim.

Let us first briefly describe the content of the π NN theory. The objective is to develop a consistent description of the following elementary π NN processes:

$$NN \rightarrow NN$$

$$\rightarrow NN\pi$$

(1.a)

$$\begin{aligned}
&\pi d \rightarrow \pi d \\
&\quad \rightarrow \pi NN \\
&\quad \rightarrow NN
\end{aligned}
\tag{1.b}$$

In Refs. 1-3, it is shown that the main features of these processes can be described to a very large extent by a meson-exchange model Hamiltonian which is constructed by extending the Paris potential⁷ to include the Δ -excitation. In Ref. 1 the excitation of $N^*(1470)$ is also included in order to account for 2π -production mechanism. To illustrate the validity of this theory, we show some typical results of Refs. 1-3 in Figs. 1-4. In Fig. 1, we see that the meson-exchange model gives a good description of NN scattering phase-shifts up to 1 GeV. The corresponding results of πd scattering and $pp \rightarrow pn\pi^+$ reactions are respectively shown in Figs. 2 and 3. It is clear that the agreements with the data are reasonable. Finally, we see in Fig. 4 that the calculated total cross sections with various spin orientations up to 2 GeV are also in fair agreement with the data.

Extending the πNN theory to include the interaction with the photon, the model Hamiltonian takes the following form

$$H = H_g + H_{em} \tag{2}$$

where H_g is the hadronic interaction for describing the πNN processes listed in Eq. (1), and H_{em} describes the coupling of photon to the πNN system

$$H_{em} = v_{\gamma N, N} + v_{\gamma N, \Delta} + v_{\gamma N, \pi N}^B \tag{3}$$

The construction of H_g has been described above. The procedure of

constructing H_{em} has been given by Tanabe and Ohta,⁸ and also by Yang.⁹ In addition to the vertex interactions $v_{\gamma N, N}$ and $v_{\gamma N, \Delta}$, it is also necessary to include a background interaction $v_{\gamma N, \pi N}^B$ to describe the elementary photo-production of pion from the nucleon.

In the one-photon approximation, the amplitude of $\gamma d \rightarrow np$ reaction defined by the model Hamiltonian Eq. (2) can be written as

$$T_{\gamma d \rightarrow np}(E) = \langle \phi_p | J^{\text{Imp}} + J^{\text{Int}} + J^{\pi} | \vec{p}_n \vec{p}_p \rangle \quad (4)$$

Each term in Eq. (4) is graphically represented in Fig. 5. They are defined as

$$J^{\text{Imp}} = \sum_{i=1}^2 v_{\gamma N, N}(i) \quad (4.a)$$

$$J^{\text{Int}} = \sum_{i=1}^2 [v_{\gamma N, N}(i) G_{NN}(E) t_{NN, NN}(E) + \tilde{v}_{\gamma N, \Delta}(i) G_{N\Delta}(E) t_{N\Delta, NN}(E)] \quad (4.b)$$

$$J^{\pi} = \sum_{i=1}^2 v_{\gamma N, \pi N}^B(i) G_{\pi NN}(E) h_{\pi N, N} \quad (4.c)$$

where G_{BB} is the baryon-baryon propagator. The impulse term Fig. 5a is determined by $v_{\gamma N, N}$ which can be calculated from the standard nucleon form factors. The interaction term, Figs. 5b and 5c, are determined by the baryon-baryon scattering t-matrix which can be generated from solving the coupled πNN scattering equation defined by the hadronic interaction H_g . The needed coupled-channel-Faddeev calculation has been discussed in Refs. 1-3.

The background interaction $v_{\gamma N, \pi N}^B$ has two leading effects. It generates the pion-exchange term Fig. 5d and also modifies the vertex interactions $\gamma N \rightarrow N$ and $\gamma N \rightarrow \Delta$. The procedure of calculating $\tilde{v}_{\gamma N, \Delta}$ in Eq. (4) from the bare vertex and the background interaction has been given by Tanabe and Ohta.⁸ To be consistent with our model of hadronic interaction H_S , we only consider their model in the case that the $\pi N P_{33}$ phase shift is fitted by using only a $\pi N \rightarrow \Delta$ vertex interaction. In this simple resonant model, the photo-nucleon vertex is only modified by the background $v_{\gamma N, \pi N}^B$, as shown graphically in Fig. 6. The interaction in other πN channels are neglected. Hence, the $\gamma N \rightarrow N$ vertex in Eq. (4) is not modified and is just calculated from the usual nucleon form factors.

In the higher energy region up to ~ 4 GeV, the theory has to be extended to include higher mass nucleon resonances and 2π and even 3π production. The starting point of the research in this direction is a πN model which can describe πN scattering up to about 2 GeV. Such a model has been recently constructed by Johnstone and Lee.¹⁰ Our effort in using this πN model to construct a meson-exchange model for NN scattering up to 4 GeV will be published elsewhere. In this work, we will only carry out calculations based on the πNN model defined by Eqs. (1)-(4). This must be sufficient for illustrating the main feature of the prediction by meson-exchange model.

With the above definitions, the $\gamma d \rightarrow np$ cross section can be calculated in the standard partial-wave representation. The formulation is tedious but straightforward, and will be published elsewhere along with our formulation of electrodisintegration of the deuteron. In the low energy limit, our theory reproduces the calculation by Friar et al.¹¹ In the Δ -excitation energy region, the theory reproduces the main features of the data. A detailed paper describing these results is being prepared.

In this short report, we compare our results with the QCD-prediction of Brodsky and Hiller.⁵ We use their notation to write the differential cross section as

$$\frac{d\sigma}{d\Omega_{c.m.}} = \frac{1}{[s(s-m_d^2)]^{1/2}} F_p^2(\hat{t}_p) F_n^2(\hat{t}_n) \frac{1}{2} \frac{|f^2(\theta_{c.m.})|^2}{P_T} \quad (5)$$

where F_n and F_p are respectively the proton and neutron form factors, P_T is the transverse momentum and m_d is the deuteron mass. The nucleon form factors in Eq. (5) are evaluated at the special kinematics that each nucleon in the deuteron carries half of the total momentum

$$\begin{aligned} \hat{t}_n^2 &= (P_n - \frac{1}{2} P_d^2)^2 \\ \hat{t}_p^2 &= (P_p^2 - \frac{1}{2} P_d^2)^2 \end{aligned} \quad (6)$$

In a simple model which resembles the $\gamma d \rightarrow np$ reaction, Brodsky and Hiller⁵ predict that the "reduced cross section" $|f|^2$ is independent of photon energy, as schematically illustrated in Fig. 7. We see in the same figure that our calculation, based on the meson theory, is clearly radically different than their hypothesis. The rising behavior of our result reflects the dependence of the $\gamma d \rightarrow np$ reaction on the relative motion of two-baryons described by the meson-exchange mechanism. In this high energy region, the short-range parameterization of the meson-exchange model is clearly an important element of our prediction. As discussed in Refs. 1-3, the conventional short-range parameterization of πNN model is probably responsible for the discrepancies between the theory and data shown in Figs. 2-4. Experimental data of $\gamma d \rightarrow np$ in the high energy region can provide additional useful information in resolving this problem.

To understand our result, it is important to note that in our approach the energy and momentum dependences of the cross section are dictated by the baryon-baryon scattering t -matrix. In the formulation of Ref. 2, one can show that

$$t(E) = V\Omega^{(+)}(E) \quad (8)$$

where V is the baryon-baryon potential calculated from the meson-exchange mechanism (as defined by the Feynman diagram). The Moller operator $\Omega^{(+)}$ is defined by an effective baryon-baryon potential which contains the coupling to pion-production channel. The detailed derivation of Eq. (8) can be found in Ref. 2 and need not be discussed here. The important point relevant to the result shown in Fig. 7 is that the coupled-channel effect contained in $\Omega^{(+)}$ depends strongly on the baryon-baryon relative angular momentum. Therefore, the predicted rising reduced cross section (solid curve) shown in Fig. 7 is different from that estimated by considering only the low order meson-exchange Feynman diagram.

Finally, we want to emphasize that the πNN theory used in our calculation has been tested against extensive NN and πd data. Similar effort must also be made in the QCD approach so that the comparison between these two different approaches can be more conclusive. Of course, at some high energy the meson-exchange model should breakdown. A precise determination of this energy region clearly needs a more consistent QCD approach which also makes contact with the existing NN and πd data. Systematic data of photo-disintegration of the deuteron certainly will be needed to test the predictions shown in Fig. 7.

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References

- ¹T.-S. H. Lee, Phys. Rev. Lett. 50, 157 (1983); Phys. Rev. C 29, 195 (1984).
- ²T.-S. H. Lee and A. Matsuyama, Phys. Rev. C 32, 516 (1985); Phys. Rev. C 32, 1986 (1985).
- ³A. Matsuyama and T.-S. H. Lee, ANL preprint (1986).
- ⁴A review of other πNN formulations was given by I. Afnan, 257C, Vol. I, Few Body Problems in Physics, ed. B. Zeithitz, North-Holland (1984).
- ⁵S. J. Brodsky and J. R. Hiller, Phys. Rev. C 28, 475 (1983).
- ⁶C. E. Carlson and F. Gross, Phys. Rev. Lett. 53, 127 (1984).
- ⁷M. Lacombe, B. Loiseau, J. M. Richard, K. Vinh Mau, J. Cote, P. Pine and R. de Turreil, Phys. Rev. C 31, 861 (1980).
- ⁸H. Tanabe and K. Ohta, Phys. Rev. C 31, 1876 (1985).
- ⁹S. N. Yang, Journal of Phys. G (1986) in press.
- ¹⁰J. Johnstone and T.-S. H. Lee, Phys. Rev. C (1986) in press.
- ¹¹J. L. Friar, B. F. Gibson and G. L. Payne, Phys. Rev. C 30, 441 (1984).

Figure Captions

- Fig. 1 NN Scattering phase shifts. Theoretical results are from Ref. 1.
- Fig. 2 πd elastic differential cross section. Theoretical curves are from Ref. 3.
- Fig. 3 $pp \rightarrow pn\pi$ cross section. Theoretical curves are from Ref. 3.
- Fig. 4 NN total cross sections. Theoretical curves are from Ref. 1.
- Fig. 5 Basic mechanisms of $\gamma d \rightarrow np$ reaction.
- Fig. 6 Renormalization of $\gamma N \rightarrow N, \Delta$ vertex by background πN interaction $V_{\gamma N, \pi N}^B$.
- Fig. 7 Compare QCD prediction (---) and the present calculation (——).

Fig. 1

π^-

Fig. 2

$$p\bar{p} \rightarrow p n \pi^+$$

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Fig. 3

Fig. 4

Fig. 5

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FIG. 6

Fig. 7