RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 49, NUMBER 2 FEBRUARY 1994

Reaction $\gamma d \to \pi^0 d$ and the small components of the deuteron wave function

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(Received 27 October 1993)

We calculate the differential cross section and the photon asymmetry of the reaction $\gamma d \to \pi^0 d$ for incident photon energies below 1 GeV and compare with data at $\theta = 130°$. Our formalism, based on the spectator-on-mass-shell approximation, is fully relativistic and uses the dNN vertex of Buck and Gross and a recently developed model for the elementary $\gamma N \to \pi N$ amplitude that describes well the first and second resonance regions. We find large sensitivity to the small components of the deuteron wave function in the energy region of the Roper resonance. Comparison to experimental data points towards a deuteron wave function with a high probability of small components.

PACS number(s): 25.20.−x, 21.45.+v, 13.60.Le

The differential cross section of the coherent pion photoproduction reaction on the deuteron $\gamma d \to \pi^0 d$ has been measured over a variety of energies and angles [1]. The photon asymmetry, on the other hand, is known only at a few points [1] and no data at all are available for the deuteron polarization observables in either the initial or final states. Previous calculations of this reaction were based in a nonrelativistic formalism [2–7], and consequently were restricted to energies below 500 MeV. In this Rapid Communication we present the first results of a fully relativistic calculation (within the spectator-on-mass-shell approximation) of the coherent pion photoproduction reaction on the deuteron. We then use these results to interpret the structure seen in experimental data on differential cross section ($d\sigma/d\Omega$) and photon asymmetry (Σ), in the region of the Roper resonance (600–700 MeV). According to our calculations, described below, this structure is the signature of the small components of the deuteron wave function.

In Fig. 1 we depict our model for the $\gamma d \to \pi^0 d$ scattering amplitude, consisting of the single (a) and double (b) scattering terms. As shown by Bosted and Laget [2] the contribution of Fig. 1(b) is very small in the first resonance region. We have found that this is true also for the second resonance region; therefore, we will only describe in detail our formalism for the single-scattering term depicted in Fig. 1(a) while our method for evaluating the diagram of Fig. 1(b) will be described in a forthcoming more extended work [8]. In the spectator-on-mass-shell approximation one evaluates the diagram of Fig. 1(a) by integrating over the fourth component of the loop momentum using Cauchy's theorem and picking up only the pole that puts the spectator particle on the mass shell [9]. Thus, the amplitude of Fig. 1(a) is given using this prescription by

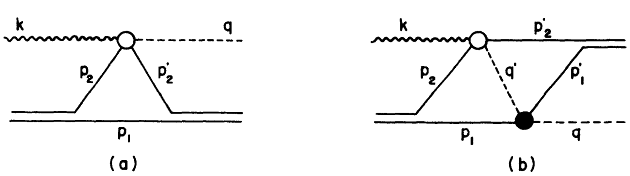

FIG. 1. The $\gamma d \to \pi^0 d$ amplitude. (a) Single-scattering term. (b) Double-scattering term.

$$A^{(a)}_{\gamma d \to \pi d} = \frac{1}{(2\pi)^3}\int \frac{M}{E_1} d\mathbf{p}_1 \bar{v}_1(\mathbf{p}_1) V^\dagger_{dNN} \frac{\not{p}_2' + M}{p_2'^2 - M^2 + i\epsilon} \times A_{\gamma N \to \pi N} \frac{\not{p}_2 + M}{p_2^2 - M^2 + i\epsilon} V_{dNN} v_1(\mathbf{p}_1), \quad (1)$$

where v_1 is a charge conjugate spinor for nucleon 1 while V_{dNN} is the dNN vertex with one nucleon off the mass shell [10]. A similar albeit somewhat longer expression is obtained for Fig. 1(b). The $\gamma N \to \pi N$ amplitude that enters in Eq. (1) was constructed in Ref. [11] and will be described later.

The dNN vertex has been studied by Buck and Gross [10] within the framework of the Gross equation of nucleon-nucleon scattering [12]. Since one nucleon is on-mass-shell the vertex has the form

$$V_{dNN} = F(p_2^2)\not{\epsilon}_d + \frac{1}{M} G(p_2^2)\epsilon_d \cdot p_1 + \frac{\not{p}_2 - M}{M}\left[H(p_2^2)\not{\epsilon}_d + \frac{1}{M} I(p_2^2)\epsilon_d \cdot p_1\right], \quad (2)$$

where ϵ_d is the polarization vector of the deuteron and p_1 and p_2 are the four-momenta of the on-shell and off-shell nucleons, respectively. The form factors F, G, H, and I are related to the two large components of the deuteron wave function u and w (corresponding to the $^3S_1$ and $^3D_1$ states) and to the two small components v_t and v_s (corresponding to the $^3P_1$ and $^1P_1$ states) as

$$F(p_2^2) = \pi\sqrt{2M_d}(2E - M_d)\left[u(p) - \frac{1}{\sqrt{2}}w(p) + \frac{M}{p}\sqrt{\frac{3}{2}}v_t(p)\right],$$

$$G(p_2^2) = \pi\sqrt{2M_d}(2E - M_d)\left[\frac{M}{E+M}u(p) + \frac{M(2E+M)}{\sqrt{2}p^2}w(p) + \frac{M}{p}\sqrt{\frac{3}{2}}v_t(p)\right],$$

$$H(p_2^2) = \pi\sqrt{2M_d}\frac{EM}{p}\sqrt{\frac{3}{2}}v_t(p), \quad (3)$$

$$I(p_2^2) = -\pi\sqrt{2M_d}\frac{M^2}{M_d}\left\{(2E - M_d)\left[\frac{1}{E+M}u(p) - \frac{E+2M}{\sqrt{2}p^2}w(p)\right] + \frac{M_d}{p}\sqrt{3}v_s(p)\right\},$$

where M_d is the mass of the deuteron, $E = \sqrt{p^2 + M^2}$, and p is the magnitude of the nucleon-nucleon relative three-momentum in the c.m. frame which is a Lorentz invariant given in terms of p_2^2 by

$$p^2 = (M_d^2 + M^2 - p_2^2)^2/4M_d^2 - M^2 . \quad (4)$$

In their study, Buck and Gross [10] used a one boson exchange (OBE) model with π, ρ, ω, and σ exchange. They used a πNN vertex which is a linear combination of pseudoscalar and pseudovector coupling as

$$V_{\pi NN} = \lambda g\gamma_5 + (1-\lambda)\frac{g}{2M}\gamma_5 \not{q} , \quad (5)$$

and considered $\lambda = 0.0, 0.2, 0.4, 0.6, 0.8$, and 1.0. In each case the parameters of the OBE model were adjusted to reproduce the static properties of the deuteron. They found that the total probability of the small components of the deuteron wave function

$$P_{\rm small} = \int_0^\infty p^2 dp[v_t^2(p) + v_s^2(p)] \quad (6)$$

increases monotonically with λ growing from approximately 0.03% for $\lambda = 0$ to approximately 1.5% for $\lambda = 1$.

In recent work [11], we constructed a model of pion electroproduction and photoproduction on the nucleon which was tested successfully for real photons in the energy region from threshold up to 1 GeV. This model of the elementary $\gamma N \to \pi N$ amplitude contains the Born terms, the vector mesons ρ and ω, and the direct and crossed diagrams of the nucleon resonances P_{33}, P_{11}, S_{11}, S_{31}, D_{13}, and D_{33}. The Born terms require only the knowledge of the γNN and πNN coupling constants which are well known. The vertices and couplings constants of the vector mesons ρ and ω are also pretty much standard nowadays [11,13,14]. Details concerning the evaluation of the direct and crossed resonance terms can be found in Ref. [11]; here we briefly mention what the basic ingredients are. The coupling constants were determined from the known phenomenology ($N^* \to \pi N$, $N^* \to \gamma N$). The crossed resonance diagrams have been regularized by means of a cutoff in the outgoing pion energy. All the possible couplings consistent with gauge invariance were taken into account. The model describes data qualitatively up to 1 GeV and quantitatively up to 800 MeV.

In Ref. [11] pseudovector coupling was considered for the Born diagrams. As discussed in Refs. [15,16] the sum of the four Born diagrams is invariant under a chiral transformation, i.e., starting from the Lagrangian appropriate to pseudovector (PV) coupling one ends up with the Lagrangian appropriate to pseudoscalar (PS) coupling by performing a chiral transformation. The resulting amplitudes are identical provided all four diagrams are transformed in a consistent way. For instance the $\gamma\pi NN$ vertex given by the pseudovector coupling Lagrangian is pseudovector while the pseudoscalar coupling Lagrangian gives a pseudotensor $\gamma\pi NN$ vertex [15,16]. Therefore for free nucleons one can use any linear combination of PS and PV couplings and get the same amplitude:

$$A_{\rm Born} = \lambda A_{\rm Born}^{\rm PS} + (1-\lambda)A_{\rm Born}^{\rm PV} . \quad (7)$$

We have checked numerically that our model satisfies this invariance for free nucleons.

In order to investigate the effect of the small components of the deuteron wave function we have calculated the differential cross section and the photon asymmetry for $\gamma d \to \pi^0 d$ as a function of energy and scattering angle. Our model gives a satisfactory description of all the available data on the $\gamma d \to \pi^0 d$ reaction at energies below 1 GeV as it will be shown in a more extended work [8]. In this Rapid Communication we will only show the results for $\theta = 130°$ because at this angle there are data for both $d\sigma/d\Omega$ and Σ; we should point out, however, that at other angles where data for $d\sigma/d\Omega$ are available, the behavior of the results is qualitatively the same. An extensive compilation of data made by the Tokyo group can be found in Ref. [1].

We show in Fig. 2 the results obtained using the $\gamma N \to \pi N$ model of Ref. [11] (pure pseudovector coupling) and varying the deuteron wave function, i.e., we calculate the observables considering the various models of Buck and Gross [10]. The experimental data show a distinctive structure in the energy region around 600–700 MeV: a minimum in Σ and a change of slope in $d\sigma/d\Omega$. This structure starts to appear gradually in the theoretical curves as one increases the parameter λ in the Buck-Gross models, that is to say, as one increases the probability of the small components in the deuteron wave function [10]. We have checked that this structure originates indeed from the small components v_t and v_s in Eqs. (2) and (3). If we make $v_t = v_s = 0$ in all the Buck-Gross models, then all the curves become very similar to

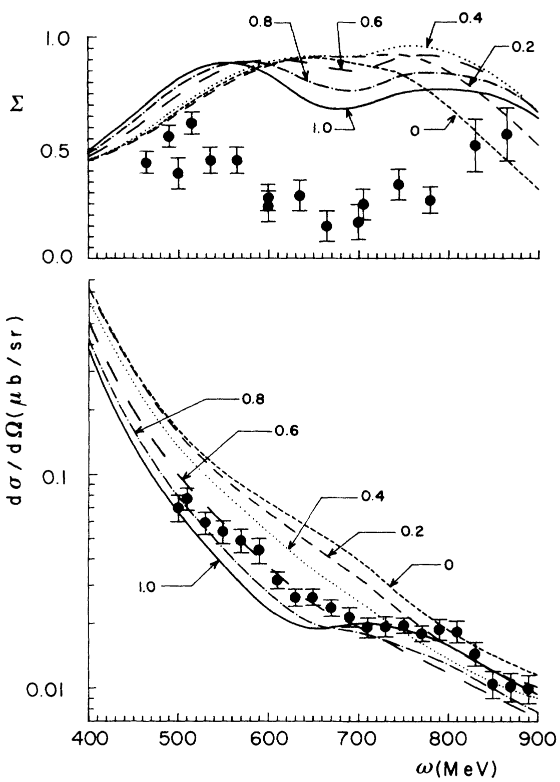

FIG. 2. Photon asymmetry (Σ) and differential cross section ($d\sigma/d\Omega$) as functions of energy for $\theta = 130^\circ$ when the parameter λ is varied in the deuteron wave function [Eq. (5)]. $\lambda = 0$ (short-dashed), $\lambda = 0.2$ (dashed), $\lambda = 0.4$ (dotted) $\lambda = 0.6$ (long-dashed), $\lambda = 0.8$ (dot-dashed), and $\lambda = 1$ (solid line). Data are from Refs. [1,17–19].

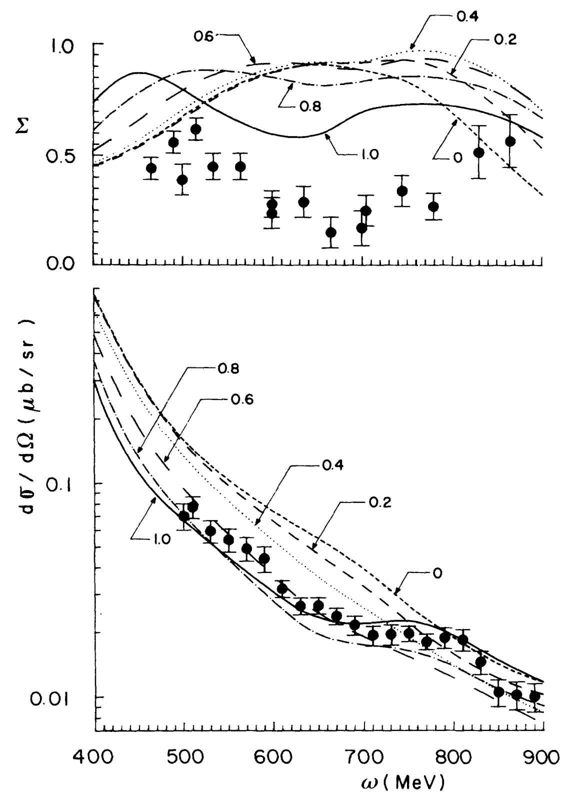

FIG. 3. Same as Fig. 2 when the parameter λ is varied simultaneously both in the deuteron wave function [Eq. (5)] and in the pion photoproduction operator [Eq. (7)].

the ones with $\lambda = 0$. Similarly, if we vary the pion photoproduction operator given by Eq. (7) by considering λ between 0 and 1 but keep the deuteron wave function constant at the Buck-Gross model with $\lambda = 0$ in Eq. (5), then again the curves change very little.

Since the different models of the deuteron wave function constructed by Buck and Gross use a πNN vertex that is a linear combination of pseudoscalar and pseudovector coupling as shown by Eq. (5), it is appealing from the point of view of consistency to use the same vertex for the elementary $\gamma N \rightarrow \pi N$ amplitude; i.e., one constructs the Born amplitudes as shown in Eq. (7) using the same value of λ as in Eq. (5). As mentioned before, our model of the elementary $\gamma N \rightarrow \pi N$ amplitude, in the case of the free nucleon, is invariant with respect to changes in λ. We show the results of this calculation in Fig. 3, where as one can see the model with $\lambda = 1$ leads to a considerably improved description of the data (remember that Σ can vary between -1.0 and 1.0).

Notice that the structure in $d\sigma/d\Omega$ and Σ arises in our calculations only when we include the small components of the deuteron wave function. These components are large when in the πNN vertex (5) $\lambda \approx 1$, i.e., when the vertex is almost pure pseudoscalar. However, this does not mean that the vertex must necessarily be pseudoscalar, since in principle, other mechanisms besides the one pion exchange could also give rise to the small components. We interpret our results as meaning that the probability of the small components of the deuteron wave function must be large ($P_{\rm small} > 1\%$).

The region around 600–700 MeV is very sensitive to the small components of the deuteron wave function. The main resonance in this energy region is the Roper resonance P_{11}. Our model for photopion production on the free nucleon is reliable in this region, in particular it gives a very good description of the electromagnetic multipoles in the channels containing the Roper resonance (see drawings for M_{1-} multipoles in Figs. 5 and 6 of Ref. [11]).

In summary, we have found that in the energy region of the Roper resonance the differential cross section and the photon asymmetry for the reaction $\gamma d \rightarrow \pi^0 d$ are highly sensitive to the small components of the deuteron wave function. In this energy region increasing the probability of the small components produces a change of slope in $d\sigma/d\Omega$ and a minimum in Σ. These two features are present in the existing experimental data. It would be interesting to measure the photon asymmetry at other angles. It would also be interesting to search for such a structure in experiments with polarized deuterons.

We would like to thank Prof. F. Gross for valuable information concerning the Buck-Gross models. This work has been supported in part by DGICYT (spain) under Contract PB92-0021-C02-01. One of us (H.G.) would like to thank the Dirección General de Investigación Científica y Técnica of the Spanish Ministry for Science and Education for a sabbatical stay (Ref. SAB92-0146).

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