Analysis of coherent pion photoproduction on the deuteron at large angles

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The differential cross section for $^2H(\gamma, \pi^0)^2H$ for photon energies from 500 to 800 MeV is calculated based on elementary processes. A comparison between calculated results and the experimental data at large angles demonstrates that double scattering becomes dominant in this region and that dibaryon resonances make no contribution to within the experimental accuracy.

As the deuteron is the simplest nucleus, experimental data for scattering from the deuteron could be interpreted more reliably than those from a heavier nucleus. In this Brief Report we use the constituent model[1] to analyze neutral pion photoproduction. This work is motivated by the fact that the experimental cross sections[2] for photons from 500 to 1000 MeV at center-of-mass angles between 90° and 130° have been measured with a statistical accuracy of ten percent. For the phenomenological amplitudes of the elementary processes, we take the Metcalf-Walker amplitudes[3] for the photopion production and use the phase shift amplitudes of Donnachie[4] for the pion-nucleon interaction. The deuteron wave function is obtained from the Paris potential.[5] We compare our results with the recent experimental data and discuss the validity of our approach.

The reaction $^2H(\gamma,\pi^0)^2H$ may be described by the diagrams shown in Fig. 1. Previous theoretical work indicates that the single scattering fails to reproduce the experimental data at large angles. To improve the situation, it is necessary to include higher-order multiple-scattering processes. Lazard *et al.* (Ref. 6) calculated the first two terms of the Watson expansion and found an improvement to the single scattering. Nakamura[7] calculated the double scattering term based on the Glauber theory. The contribution of the double scattering term becomes dominant in the kinematical region covered by the experiment of Ref. 2. Their result reproduced the observed data fairly well except when the photon energy was near 700 MeV.

The notation used for kinematical variables is defined in Fig. 1. In this calculation we use the following. (1) The deuteron four-dimensional wave function is defined as a product of the two constituent nucleon wave functions. With these wave functions we can write the invariant amplitude for the process described by Fig. 1. (2) The constituent nucleon wave function is decomposed into a space-time part and a Dirac spinor $u(p)$. (3) The space-time part is alternatively expressed by a product of the center-of-mass wave function of the deuteron and the relative one $\phi(p,r)$. (4) The center-of-mass part is a plane wave while the relative wave function is given by

$$\phi(p,r)=\exp(-i\epsilon_p t)V^{1/2}\phi(\mathbf{r}) \ , \tag{1}$$

where ϵ_p is the energy of the relative system, t is time, V is a normalization volume, and $\phi(\mathbf{r})$ is the ordinary deuteron wave function with the space coordinate $\mathbf{r}$. (5) The noninteracting line is unity if $q_2=k_2=p_2$.

The diagrams of Fig. 1(a) reduce to a single amplitude M_1,

$$M_1=\int \frac{d^3k}{(2\pi)^3} f(\gamma N\to\pi N)\zeta^*(\mathbf{k}-\mathbf{b}/2)\zeta(\mathbf{k}-\mathbf{a}/2) \ , \tag{2}$$

with $\mathbf{k}=(\mathbf{k}_1-\mathbf{k}_2)/2$ and

$$\zeta(\mathbf{k}-\mathbf{a}/2)=\int d^3r\, \phi(\mathbf{r})\exp[-i(\mathbf{k}-\mathbf{a}/2)\cdot\mathbf{r}] \ .$$

In Eq. (2), $f(\gamma N\to\pi N)$ is the single-pion photoproduc-

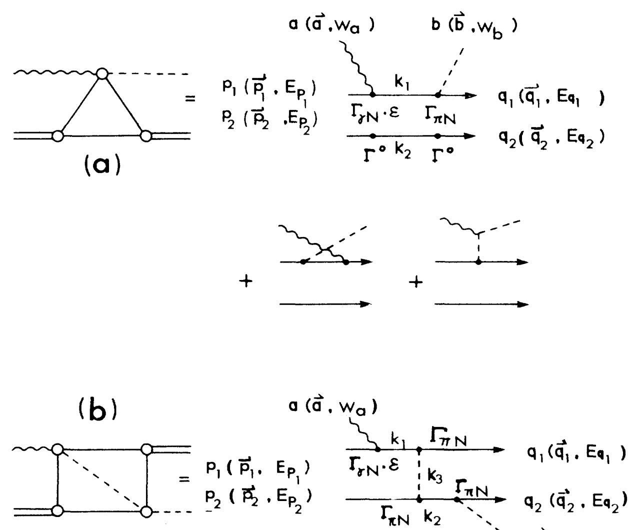

FIG. 1. Diagrams involved in the reaction; (a) the single scattering term, and (b) the double scattering term. The kinematical variables which are used in the present calculation are also defined.

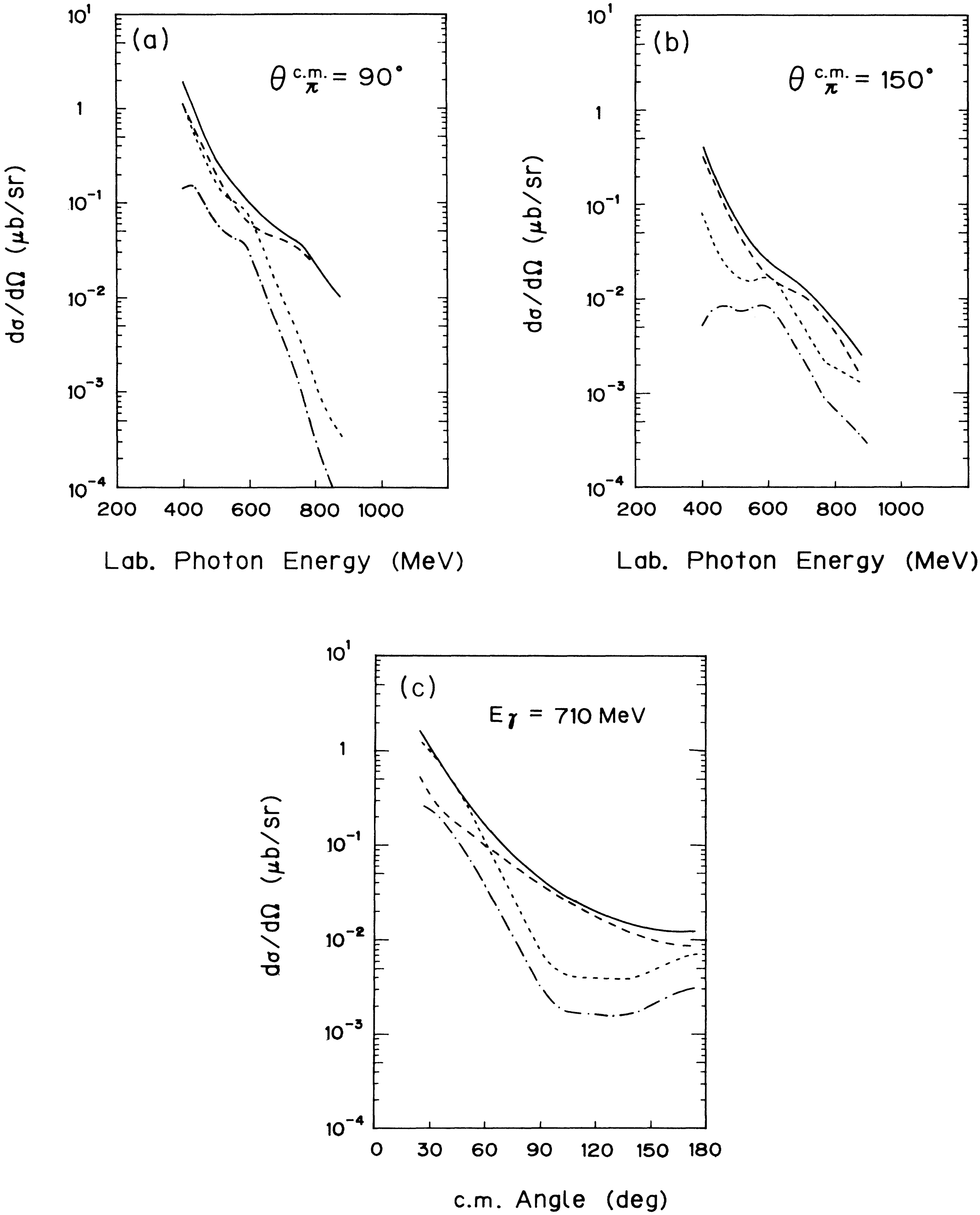

FIG. 2. Energy dependence of the differential cross sections at center-of-mass angles (a) 90° and (b) 150°. In (c) the differential cross section for a photon energy of 710 MeV is presented. The lines denote the following: short dash, single scattering term; long dash, double scattering term; dash-dot, interference term; solid, sum of those terms.

tion amplitude for a free nucleon

$$f(\gamma N \to \pi N) = \bar{u}(q_1)\Gamma_{\pi N} iS(k_1)\Gamma_{\gamma N}\epsilon u(p_1) , \quad (3)$$

where $\Gamma_{\pi N}$ and $\Gamma_{\gamma N}\epsilon$ are the vertices for π-N-N and γ-N-N scatterings, respectively, and $iS(k_1)$ is the baryon propagator. The double scattering amplitude M_2 is

$$M_2 = \int \frac{d^3k}{(2\pi)^3} f(\pi N \to \pi N) \frac{i}{k_3^2 - m_\pi^2 + i\epsilon} \times f(\gamma N \to \pi N) \zeta^* \left[\mathbf{k} + \frac{\mathbf{b}}{2} - \frac{\mathbf{k}_3}{2} \right] \zeta \left[\mathbf{k} - \frac{a}{2} - \frac{\mathbf{k}_3}{2} \right] , \quad (4)$$

where $\mathbf{k}_3 = (\mathbf{a}+\mathbf{b})/2 + \mathbf{p} - \mathbf{q}$, m_π is the pion mass, and $f(\pi N \to \pi N)$ is the pion-nucleon amplitudes. The total amplitude M is given by the sum of M_1 and M_2,

$$M = (2\pi)^3 \delta^3(\mathbf{p}_2 - \mathbf{q}_2) M_1 + M_2 . \quad (5)$$

The differential cross section may then be expressed as

$$\frac{d\sigma}{d\Omega} = \int \frac{d^3q}{(2\pi)^3} \frac{d^3p}{(2\pi)^3} \frac{1}{|\mathbf{v}|} \left[\frac{m_N^2}{4\pi} \right]^2 \tfrac{1}{6} \Sigma |M|^2 \times \frac{w_Q}{w_a(w_a + w_P) E_{p_1} E_{p_2} E_{q_1} E_{q_2}} , \quad (6)$$

with nucleon mass m_N, relative velocity $\mathbf{v}$, $2p = p_1 - p_2$, $2q = q_1 - q_2$, $P = p_1 + p_2$, and $Q = q_1 + q_2$.

In computing the differential cross section (6), we introduce a cutoff momentum to calculate the loop integration in M_2. The cutoff parameter is determined so as to reproduce the experimental data at 110°.

The energy dependence of the differential cross section for center-of-mass angles 90° and 150° is shown in Figs. 2(a) and (b), respectively. The differential cross section at 710 MeV is also depicted in Fig. 2(c). In this figure the contributions of each term in Fig. 1 and the interference term are also shown. From this work, the following general features may be observed. (1) The contribution of the single scattering term is the same order of magnitude as that of the double scattering term for energies below 600 MeV. (2) Above 600 MeV, the double scattering process becomes dominant. This trend is enhanced if one also increases the scattering angle. (3) The interference term is not so important as the other two terms.

The theoretical results are compared with the experimental data in Fig. 3. Within experimental accuracy, we find good agreement between theory and experiment in the angular region from 90° to 130° and photon energies between 500 and 800 MeV. In this kinematical region, there appears to be no need for additional processes. In the energy region above 800 MeV, however, there exists a significant discrepancy. In this energy region, however, the free pion photoproduction amplitude is not known and one may also be sensitive to the short distance part of the deuteron wave function.

We conclude with the following. (1) The constituent model works well for the coherent pion photoproduction at large angles. (2) The experimental results up to 800 MeV are reproduced by using the available data for the

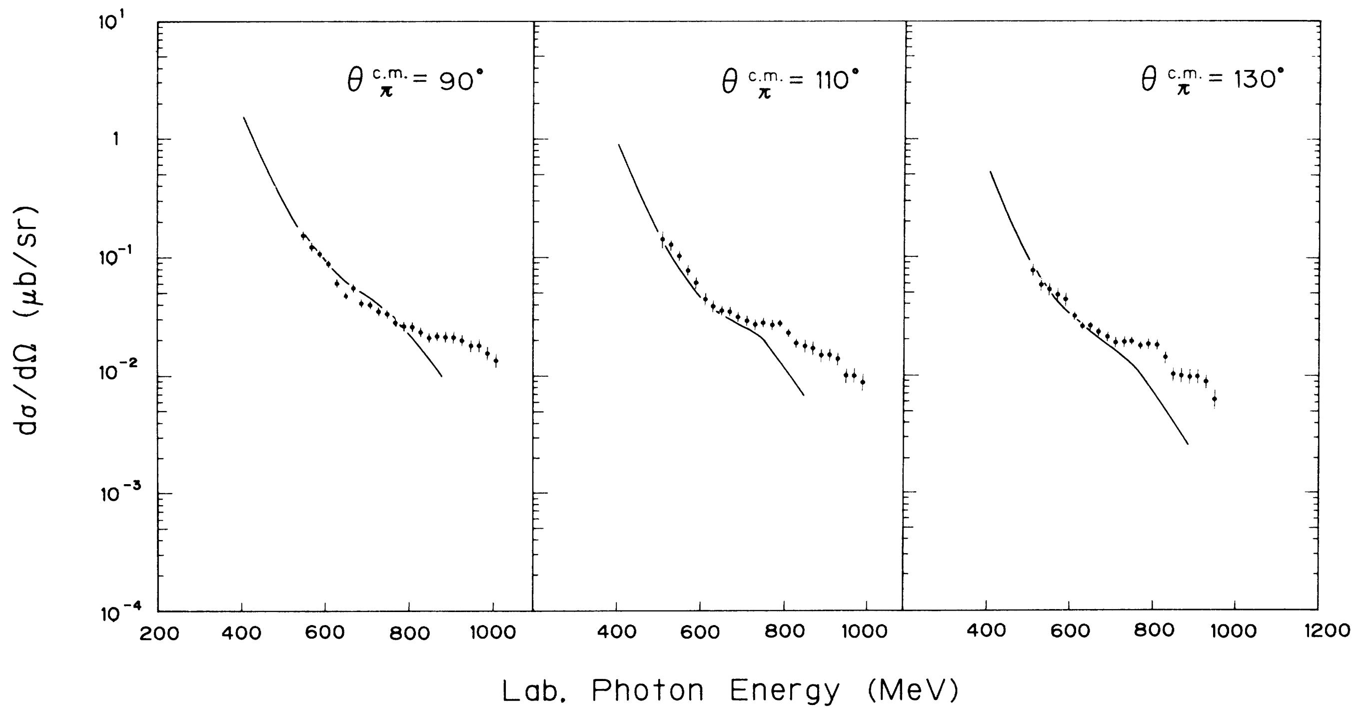

FIG. 3. Comparison of the present results with the experimental data of Ref. 2.

elementary processes and a physical deuteron wave function. Consequently, there are no indications of any dibaryon resonances[8] from data with photon energies between 500 and 800 MeV. (3) As the Paris potential was used in the calculations, we get a similar result using the Reid soft core potential.[9] (4) Given the ambiguities of going above 800 MeV, additional tests of these results require data at even larger angles.

The numerical computation was performed by the central computer FACOM 380 of Institute for Nuclear Study, University of Tokyo.

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