Reaction $D(\gamma,pp)\pi^-$ for High Values of the Emitted Nucleon Momenta

P. E. Argan, G. Audit, A. Bloch, J. L. Faure, J. M. Laget, J. Martin, G. Tamas, and E. Vincent
Département de Physique Nucléaire, Commissariat d'Etudes Nucléaires de Saclay, 91190 Gif-sur-Yvette, France
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By detecting in coincidence the two emitted protons, we have studied the reaction $D(\gamma,pp)\pi^-$ in a kinematical region where the pion-nucleon single-rescattering mechanism is dominant. We have also observed the onset of the photoproduction of two pions on one nucleon followed by the reabsorption of one of them by the other nucleon.

Significant deviations (~20%) from the predictions of the spectator-nucleon model (diagrams I in Fig. 1) have been recently observed[1] in the yield of the reaction $D(\gamma,p\pi^-)p$, when the spectator-nucleon momentum reaches $p_s \sim 150$ MeV/c. They have been analyzed as the consequences of pion-nucleon and nucleon-nucleon rescattering amplitudes which interfere with the still dominant quasifree pion photoproduction background.[2] The summation of several diagrams was needed to reproduce the data and did not allow us to select clearly and study in detail the effects of each specific mechanism.

Among them the pion-nucleon single-rescattering diagram (II, in Fig. 1) is of particular interest[3] in view of its close connection with the pion-exchange term in the ΔN interaction (compare diagrams IIb and III in Fig. 1). It is also responsible for the excess of events found in the high-momentum tail of the spectator-nucleon distribution measured in bubble chamber experiments.[4] However, good agreement for this integrated quantity checks only the order of magnitude of its effect: The lack of statistics in these measurements precludes the analysis of differential cross sections for high values of the emitted nucleon momenta.

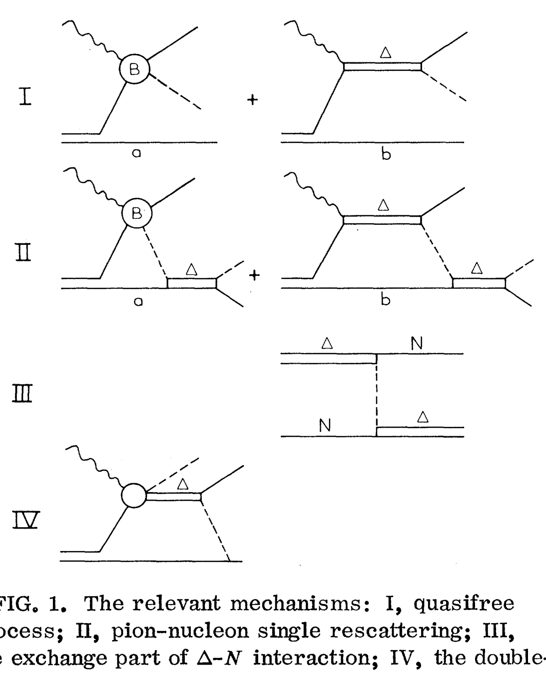

FIG. 1. The relevant mechanisms: I, quasifree process; II, pion-nucleon single rescattering; III, the exchange part of Δ-N interaction; IV, the double-pion-photoproduction mechanism. The blobs labeled B stand for the Born terms in the elementary operator for single photoproduction on nucleon.

To study it in more detail we have measured with good statistical accuracy the yield of the $\gamma D \to pp\pi^-$ reaction, in an experiment where the kinematics are completely defined. We have obtained the angular distribution of one of the emitted protons, keeping its momentum constant ($p_2 = 400$ MeV/c) at a value high enough to suppress appreciably the quasifree contribution. We have also set constant the invariant mass ($Q = 1200$ MeV) of the remaining system (the pion and the other proton), and the angle ($\omega = 90°$) between the pion and the incoming photon measured in the c.m. frame of this π-N pair. Consequently the small contribution due to the spectator-nucleon model is isotropic. Moreover the large relative kinetic energy of the two outgoing nucleons ($T_L \sim 200$–300 MeV) suppresses their final-state interactions. A more detailed discussion of the advantage of these kinematical conditions can be found in Refs. 1 and 2.

We use the same experimental setup as in the previous study of the reaction $D(\gamma,p\pi^-)p$ for lower values of the undetected nucleon momentum.[1] Instead of a pion-proton pair, we now detect the two protons, in coincidence, taking advantage of their higher energies. Two important consequences immediately follow: The troubles due to the muon contamination[1] are avoided, and the experimental phase space defined by the detectors is greater. Hence smaller cross sections can be measured.

The bremsstrahlung beam of the 600-MeV Saclay linac strikes a 2-cm-thick liquid deuterium target. The bremsstrahlung endpoint is always chosen in such a way that only one pion emerges in the final state. One proton, the momentum of which is kept constant, is detected in a range telescope ($\Delta\Omega \sim 12$ msr) and the other in a magnetic spectrometer (maximum momentum 700 MeV/c, $\Delta\Omega \sim 2.3$ msr). The particles are identified by the analysis of their energy losses in two counters in each detector. The total energy lost in the telescope is also recorded. The separation between the protons and the pions is good in both arms (see Ref. 1). In the telescope a possible neutron contamination from the $\gamma D \to pn$ reaction is avoided, since the opening angle between the two detectors is always around 120°, a value which is very different from the angle of about 170° required by the two-body nature of this background reaction.

Since the momentum of the proton detected in the telescope is constant, the corrections due to multiple scattering or nuclear absorption in the copper absorber and the scintillators is the same for the whole angular distribution. We determined this overall normalization by measuring the yield of the reaction $D(\gamma, p_1\pi^-)p_s$ for a spectator-nucleon momentum near $p_s \sim 50$ MeV/c: We detected the pion in the magnetic spectrometer and the proton, with momentum $P_1 = 400$ MeV/c, in the telescope. The result was compared to our previous measurement.[1]

TABLE I. The experimental conditions and the measured yields.

Q MeV	p_2 MeV/c	θ_2 deg	p_1 MeV/c	θ_1 deg	$\Delta N/\Delta\Omega_1\Delta\Omega_2\Delta p_1\Delta p_2$ 10^{-5} $\mu b/(Sr^2 MeV^2)$ a	b	c
1200	400	30	359	−83	.21	.53	1.23 ± .23
		40	414	−76.5	.25	.45	2.19 ± .19
		50	470	−70	.30	.41	2.51 ± .23
		60	528	−63.9	.34	.40	1.85 ± .15
		70	588	−57.7	.37	.38	1.76 ± .12
		80	651	−51.8	.43	.42	1.56 ± .09
1100	550	37.5	380	−93.5	.078	.313	1.62 ± .38
		42.5	380	−93.5	.085	.301	3.48 ± .54
		47.5	441	−82.3	.093	.248	1.93 ± .21
		52.5	441	−82.3	0.101	.252	2.61 ± .24
		57.5	509	−72	.112	.216	2.86 ± .27
		62.5	509	−72	.125	.221	3.85 ± .32
		67.5	585	−62.5	.136	.195	3.46 ± .33
		72.5	585	−62.5	.159	.204	4.21 ± .42

[a]Spectator-nucleon model without Pauli corrections.
[b]Spectator-nucleon model with Pauli corrections.
[c]Experimental values.

We give in Table I the values of the measured yield per equivalent quantum, and compare it to the prediction of the spectator-nucleon model with and without Pauli corrections (the slope in those yields, when θ_2 increases, comes exclusively from the phase-space variation). We refer the reader to Ref. 2 (especially Fig. 11) for the details of this calculation, the only change from which concerns the deuteron wave function: We use now a parametrization of the Reid soft-core wave function (see Bosted and Laget,[5] appendix) which is more accurate for high-momentum values. Because the experimental phase space is large we have integrated these theoretical cross sections by a Monte Carlo procedure as explained in Ref. 1. However this averaging does not affect significantly the results (~10%) and, to a first approximation, it is possible to use the predictions of the model computed with the central values of the momenta and the angles.

The Pauli corrections are important for small values of the angle θ_2, where the momenta of each nucleon become comparable. In order to exhibit the importance of the two-nucleon effects, we have plotted in Fig. 2(a) the ratio of the measured yield to the yield we should have measured

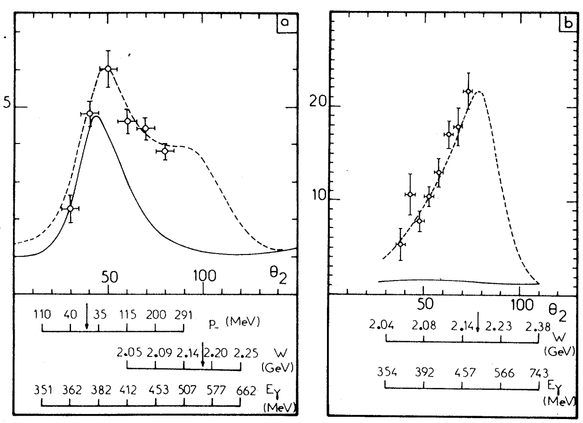

FIG. 2. (a) The ratio of the measured yields to the yield computed when only one-nucleon mechanisms are considered. The solid-line curve includes the pion-nucleon single-rescattering mechanism and the broken-line curve includes also the double-pion-photoproduction mechanism. The experimental conditions are $p_2 = 400$ MeV/c, $Q = 1200$ MeV, and $\omega = 90°$. The arrow on the scale of the lower bound p_- for a physical rescattering shows the origin. The arrow on the scale of the two-nucleon invariant mass shows the value $W = M + m$. The energy E_γ of the incoming photon is also plotted as the abscissa. (b) The same as in (a) but for $p_2 = 550$ MeV/c, $Q = 1100$ MeV, and $\omega = 90°$.

if only one-nucleon processes were relevant (spectator model with Pauli corrections, column b in Table I). A peak clearly appears near $\theta_2 \sim 45°$ as predicted by the model[2] which includes the dominant contribution due to the pion-nucleon rescattering diagram (II in Fig. 1). Since the energy available at the scattering vertex is larger than the sum of the masses of the interacting particles, the internal pion can propagate on its mass shell, and the matrix element develops a logarithmic singularity. Its effect is maximum when the allowed kinematical region for a physical scattering is the widest, i.e., when the lower bound p_- of this physical region goes through zero, as indicated on the abscissa of Fig. 2(a). The dominance of this pion-nucleon rescattering mechanism and the smallness of the corrections due to the multiple scattering of the pion (as predicted in Ref. 2) are strongly supported by our experiment.

However, a significant departure appears for larger values of θ_2, where the contribution of the pion-nucleon single rescattering diagram falls off more quickly than the experimental data. This excess of cross section is consistent with the onset of the photoproduction of two pions on one nucleon followed by the reabsorption of one of them by the other nucleon (diagram IV in Fig. 1). The double pion photoproduction on a free nucleon[6] is well understood in terms of the creation of one pion and a $\Delta(1236)$: This model[7] reproduces fairly well the rapid rise in the total cross section between $E_\gamma \simeq 400$ MeV and $E_\gamma \simeq 600$ MeV. Clearly the contribution of this process to the $D(\gamma,pp)\pi^-$ cross section is expected to be maximum when the invariant mass W of the two protons is close to the sum of the masses of the $\Delta(1236)$ and the nucleon ($W \simeq 2170$ MeV). A detailed description of this model and a discussion of the choice of the relevant parameters are given by Laget,[8] and we show in Fig. 2(a) the net result.

As this double-pion-photoproduction mechanism is also involved in the interpretation of the reaction $^4He(\gamma,p\pi^-)$,[9] we have isolated its contribution to check the validity of the corresponding model. We have repeated the measurement of the angular distribution of one of the outgoing nucleons for the following values: $p_2 = 550$ MeV/c, $Q = 1100$ MeV, and $\omega = 90°$. The results are depicted in Fig. 2(b). Both the quasifree process (higher value of the spectator-nucleon momentum) and the pion-nucleon single-rescattering mechanism (small contribution of the Δ at the rescattering vertex and vanishing kinematical region for on-shell rescattering) are strongly suppressed. The pion is emitted at rest in the laboratory system, minimizing the energy of the photon for which the invariant mass of the two nucleons becomes close to $W = 2170$ MeV: It falls now in the energy range of the Saclay linac. The agreement between the experiment and the model is excellent and it is worthwhile noting that the same set of parameters[8] leads also to a good accounting for the $\pi^+D \rightarrow pp$ [10] and the $\gamma D \rightarrow pn$ [11] reaction cross sections in the $\Delta(1236)$ region. Since the dynamics of these three reactions are the same, the two-pion mechanism in the reaction $D(\gamma,pp)\pi^-$ seems to be firmly established. Unfortunately the maximum energy presently available at the high-duty-cycle electron linac is not sufficient and the study of the falloff of the cross section above $W = 2170$ MeV must await a new generation of machines.

Let us now summarize the main results of this study. We have worked near the region of maximum singularity of the pion-nucleon single-rescattering diagram. As far as we know, this is the first time that the exchange part of the Δ-N interaction has been directly studied in an experiment. We have confirmed that the single- (real) pion-exchange Born term (diagram III in Fig. 1) is dominant: The corresponding logarithmic singularity, in the yield of the reaction $\gamma D \rightarrow pp\pi^-$, has never been seen before in a reaction induced by an intermediate-energy probe. This result is a strong constraint for nuclear-physics calculations in which this Δ-N potential enters as an input. We have also studied the effects of the double pion photoproduction on the yield of the reaction $\gamma D \rightarrow pp\pi^-$. This mechanism can also be viewed as a meson-exchange-current correction at the vertex describing the single-pion photoproduction on a nucleon. With use of the successful description of this mechanism, in a region where it is dominant, it is now possible to look for its effects in other pion photoproduction reactions on nuclei.

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Double Pion Photoproduction on One Nucleon and the Reaction $\gamma D \to pp\pi^-$

J. M. Laget
Département de Physique Nucléaire, Centre d'Etudes Nucléaires de Saclay, 91190 Gif-sur-Yvette, France
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I evaluate the contribution, to the cross section for the reaction $\gamma D \to pp\pi^-$, of the mechanism in which one of the two pions created at one nucleon is reabsorbed by the other.

Double-pion-photoproduction reactions on free nucleons have been extensively studied in several bubble chamber experiments.[1-4] The total reaction cross section exhibits a rapid rise as the incident photon energy increases from $E_\gamma \simeq 400$ MeV to $E_\gamma \simeq 600$ MeV, where it reaches a broad maximum. This characteristic feature is well understood as the threshold creation (in an S state) of a π-$\Delta(1236)$ pair.[5] This isobar model reproduces the behavior and the magnitude of the total cross section and also the shape of the decay distribution. A comprehensive review can be found in Lüke and Söding.[6] The two most important contributions come from the contact term [diagram (Ia) in Fig. 1] and the photoelectric term [diagram (Ib)] which account, respectively, for about 75% and 25% of the cross section. Other diagrams [(Ic), (Id)] are necessary for gauge invariance, but do not play a significant role in the cross section. Above $E_\gamma \simeq 700$ MeV the resonant production of the π-Δ pair [diagram (Ie)] begins to appear and absorptive corrections must be considered.

The cross section for the emission of two pions (~80 μb at $E_\gamma \simeq 600$ MeV) is of the same order of magnitude as the cross section for single-pion photoproduction (~200–300 μb at 300 MeV, ~100 μb at 600 MeV). Therefore it is likely that the mechanism, in which one of the two pions created at one nucleon is reabsorbed by the other nucleon [diagrams (IIa), (IIb)], leads to a contribution comparable to the pion-nucleon rescattering mechanism [diagram (III)] in the $\gamma D \to pp\pi^-$ reaction, or the pion reabsorption mechanism [diagram (IV)] in the $\gamma D \to pn$ reaction. Indeed it possibly has been observed[7] recently in the yield of the $\gamma D \to pp\pi^-$ reaction and it must also be considered to explain the excess measured, at high momentum of the recoiling system, in the $^4He(\gamma, p\pi^-)$ reaction.[8]

Let us begin with the discussion of the isobar model for the $\gamma N \to N\pi\pi$ reaction. I follow the same method and the same notation as in the case of the $\gamma N \to N\pi$ reaction.[9] I compute the nonrelativistic limit of each matrix element, keeping only terms up to the order p^2/m^2. I deduce the new $\gamma N\Delta\pi$ contact Lagrangian by making the minimal substitution in the $\pi\Delta N$ Lagrangian. The elementary cross section takes the form

$$T_{\gamma N \to N\pi\pi}(\vec{p}_i, m_i, \vec{p}_f, m_f) = -C \frac{eG_3^2}{R^0 - E_R + i\Gamma/2} (m_f | \vec{S} \cdot \left[\vec{q} - \frac{q^0}{M_\Delta} \vec{R} \right] \vec{S}^+ \cdot \left[\vec{\epsilon} + \frac{2\vec{\mu} \cdot \vec{\epsilon}}{(\mu - k)^2 - m_\pi^2 + i\eta} (\vec{\mu} - \vec{k}) \right] | m_i), \quad (1)$$

where $R^0 = k + p_i^0 - \mu^0$ is the actual energy of the intermediate Δ and $E_R = [M_\Delta^2 + (\vec{k} + \vec{p}_i - \vec{\mu})^2]^{1/2}$ its on-shell energy. The operator $\vec{S}$ connects spin-$\frac{3}{2}$ states and spin-$\frac{1}{2}$ states and is defined in Ref. 9. The photon polarization vector is $\vec{\epsilon}$. The momentum of each particle is labeled in Fig. 1. Clearly the first amplitude in the right-hand side comes from the contact term and the second amplitude from the photoelectric term. The values of the coupling constant G_3, the mass M_Δ, and the width Γ of the Δ are giv-

