Collaboration, Phys. Rev. 175, 1669 (1968); F. Carbonara *et al.*, Nuovo Cimento 36A, 219 (1976).
[7]D. Lüke *et al.*, Nuovo Cimento 28A, 234 (1968).
[8]J. M. Laget, following Letter [Phys. Rev. Lett. 41, 89 (1978).
[9]P. E. Argan *et al.*, to be published, and in *Proceedings of the International Conference on High Energy Physics and Nuclear Structure, Zürich, 1977*, edited by M. P. Locher (Birkhauser-Verlag, Basel, Switzerland, 1978), communication D1.
[10]M. Brack *et al.*, Nucl. Phys. A287, 425 (1977).
[11]J. M. Laget, to be published.

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

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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 $^4\mathrm{He}(\gamma, p\pi^-)$ 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

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

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 given by Blomqvist and Laget[9] and Laget.[10] Isospin coefficient is $C=1$ for the reaction $\gamma p \to \pi^-\Delta^{++}[p\pi^+]$, $C=-\sqrt{2}/3$ for the $\gamma n \to \pi^-\Delta^+[p\pi^0]$ and $C=\frac{1}{3}$ for the reaction $\gamma p \to \pi^+\Delta^0[p\pi^-]$ (the particles inside the bracket indicate the Δ decay mode).

The matrix element of the dominant diagram (IIa) is

$$T(\vec{k},\vec{\epsilon},M,\vec{p}_1,m_1,\vec{p}_2,m_2)=+\frac{g_0}{2m}\sum_{m_n m_p}\int\frac{d^3p}{(2\pi)^3}(m_2|\vec{\sigma}\cdot(\vec{p}_2-\vec{p})|m_p)$$
$$\times\left\{\frac{1}{\sqrt{4\pi}}u_0(p)(\tfrac{1}{2}m_n\,\tfrac{1}{2}m_p|\,1M)+u_2(p)\sum_{m_l}(\tfrac{1}{2}m_n\,\tfrac{1}{2}m_p|\,1m_s)(2m_l\,1m_s|\,1M)Y_2^{m_l}(\hat{p})\right\}$$
$$\times\frac{\sqrt{2}T(\gamma p\to\pi^-\Delta^{++}[p\pi^+])-T(\gamma n\to\pi^-\Delta^+[p\pi^0])}{q^2-m_\pi^2+i\eta},\qquad(2)$$

where $u_0(p)$ and $u_2(p)$ are, respectively, the S and D part of the deuteron wave function. Those coming from the Reid soft-core potential[11] are used in the calculation. The integral in Eq. (2) which takes the Fermi motion fully into account is computed exactly by a numerical method. The conservation of energies and momenta is assumed at each vertex.

The calculation of the diagram (IIb) proceeds analogously and I do not give here the expression for the corresponding matrix element. However, it does not contribute very much to the cross section of the $\gamma D \to pp\pi^-$ reaction, because the only allowed elementary reaction is $\gamma p \to \pi^+\Delta^0[p\pi^-]$. The overall isospin coefficient is $\sqrt{2}/3$, a value 4 times smaller than the overall isospin coefficient $(4\sqrt{2}/3)$ arising from the combination of elementary amplitudes in Eq. (2).

The two-pion-mechanism contribution is expected to be strongest when the invariant mass W of the two outgoing nucleons is close to the sum of the masses of the nucleon and the $\Delta(1236)$ ($W \sim 2170$ MeV). This appears clearly in Fig. 2 where I compare the prediction of the model to the experimental data[7] obtained in a kinematical region where both the quasifree background (high value of the nucleon momenta) and the pion-nucleon rescattering mechanism (I have added the S-wave π-N scattering to the small resonant π-N scattering computed in Ref. 10) have been strongly reduced. I present the angular distribution of

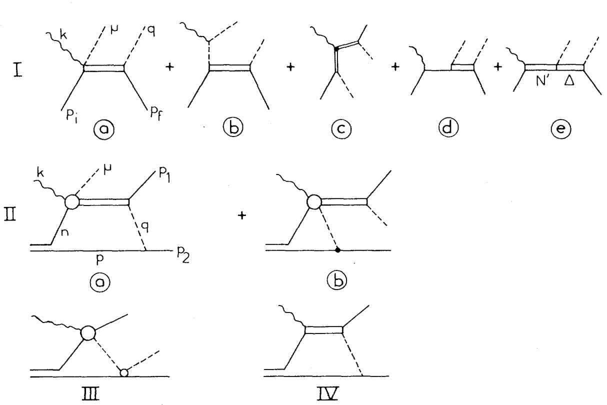

FIG. 1. The relevant diagrams for describing (I) the $\gamma N \to N\pi\pi$ reaction, (II) the double pion photoproduction, and (III) the pion-nucleon single-rescattering mechanism in the $\gamma D \to pp\pi^-$ reaction, and (IV) the pion reabsorption mechanism in the $\gamma D \to pn$ reaction.

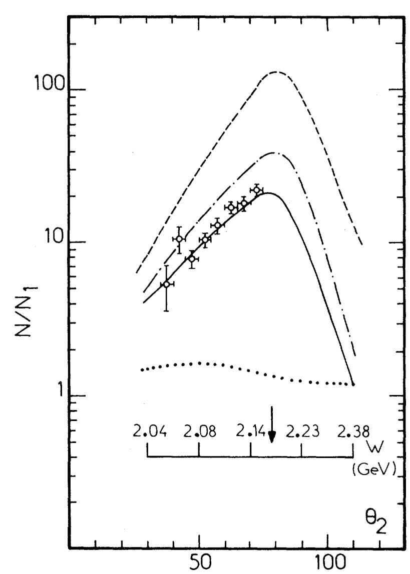

FIG. 2. The ratio of the cross section predicted by our model to the cross section which would have been obtained if only the processes involving one nucleon were present. Dotted line curve: pion-nucleon and nucleon-nucleon single-rescattering mechanism included. The other three curves are obtained when the double-pion-photoproduction mechanism is also included, with (full line curve) or without (broken line curve) form factors and ρ-exchange contribution, and with only form factors (dash-dotted line curve). The experimental points (Ref. 7) have been obtained for the following kinematics: $Q = 1100$ MeV, $p_2 = 550$ MeV/c, and $\omega = 90°$. The arrow on the two-nucleon mass W abscissa shows the sum of the nucleon and the Δ masses.

one nucleon emitted with a constant momenta $p_2 = 550$ MeV/c, when the mass of the system made of the pion and the other one is $Q = 1100$ MeV and when the pion angle is also constant $\omega = 90°$. I have plotted the ratio of the cross sections (theoretical or experimental) to the cross section expected from one-nucleon processes alone. However, as noted in the analysis of the $\pi^+D \to pp$ [12] and the $\gamma D \to pn$ [13] reactions, the magnitude of this effect is too large. The reason lies in the fact that the exchanged pion is very far from its mass shell: A form factor is needed at each pion-baryon vertex and the ρ-exchange mechanism should also be considered.

Use of a monopole form factor $[F_\pi(q^2) = (\Lambda_\pi^2 - m_\pi^2)/(\Lambda_\pi^2 - q^2)]$ at each pion-baryon vertex, with a cutoff mass $\Lambda_\pi = 1$ GeV consistent with the dispersion analysis of the πNN vertex,[14] significantly lowers the cross section. The remaining discrepancy is accounted for by allowing the ρ to be exchanged. Since its squared four-momentum is several time the squared pion mass, the denominators $(q^2 - m_\pi^2)$ in the pion propagator and $(q^2 - m_\rho^2)$ in the ρ propagator are comparable: If the ρ-baryon coupling constant is not negligible, the ρ-exchange amplitude contributes also to the cross section. Its expression is easily deduced from Eqs. (1) and (2) by making the following substitution:

$$\frac{\vec{S}\cdot\vec{q}\,\vec{\sigma}\cdot\vec{q}}{q^2 - m_\pi^2} \to \frac{(\vec{S}\times\vec{q})\cdot(\vec{\sigma}\times\vec{q})}{q^2 - m_\rho^2}\,\frac{G_\rho^2}{G_\pi^2} = \frac{G_\rho^2}{G_\pi^2}\left[-\frac{\vec{S}\cdot\vec{q}\,\vec{\sigma}\cdot\vec{q}}{q^2 - m_\rho^2} + \frac{q^2\vec{S}\cdot\vec{\sigma}}{q^2 - m_\rho^2}\right], \qquad (3)$$

where G_ρ^2/G_π^2 stands for the ratio of the product of the relevant coupling constant at the ρ-baryon and π-baryon vertices. Assuming

$$g_{\rho\Delta N}/g_{\rho NN} \equiv g_{\pi\Delta N}/g_{\pi NN} \text{ (quark model)},$$

one can write

$$G_\rho^2/G_\pi^2 = g_{\rho NN}^2(1+K_V)^2/g_{\pi NN}^2.$$

Good agreement with the data is obtained with $G_\rho^2/G_\pi^2 = 1.3$: i.e., $g_{\rho NN}^2/4\pi = 0.86$ and $K_V = 3.6$ as deduced from the nucleon-nucleon scattering analysis.[15] At each ρ-baryon vertex a form factor of the dipole type,

$$|F_\rho(q^2)| = [(\Lambda_\rho^2 - m_\rho^2)/(\Lambda_\rho^2 - q^2)]^2,$$

with the cutoff mass $\Lambda_\rho = 2m$ ($m = 938.3$ MeV), is used consistently with the analysis of the electromagnetic form factors of the nucleon.[16] The intermediate $\Delta(1236)$-nucleon pair is essentially in an $^5S_2$ state, and the two nucleons are emitted in a $^1D_2$ state. Therefore the spin-spin part of the ρ-exchange amplitude contributes little to the cross section[12] and the overall effect of the tensor part is equivalent to an additional form factor. Alternatively the data can also be fitted as well, without considering the ρ-exchange mechanism, if a dipole form factor ($\Lambda_\pi = 1$ GeV) is used at each pion-baryon vertex. The effects of the uncertainty in the choice of the ρ-baryon coupling constant can be compensated by a slight modification of the cutoff mass in the π-baryon form factors.

The success of this model in reproducing also the $\gamma D \to pn$ reaction cross section (with the same set of parameters[13]) and the $\pi^+D \to pp$ reaction cross section (the different values $G_\rho^2/G_\pi^2 \sim 1.3$ and $\Lambda_\pi \sim 1.2$ GeV [12] can be accounted for by a slightly different choice for the $\pi\Delta N$ coupling constant) gives me some confidence in the analysis of the $\gamma D \to pp\pi^-$ reaction reported here: The same transition $[^5S_2(\Delta N) \to {}^1D_2(NN)]$ dominates in each reaction. However, this $\Delta N \to NN$ transition amplitude is described, as the Born term of one-boson ($\pi + \rho$) exchange model, in a way which violates unitarity. My reasonable guess for the values of the $\rho\Delta N$ and ρNN coupling constants and for the cutoff mass in the form factors (which are not known with enough accuracy) might mock up the necessary unitary corrections to this amplitude. A way to fulfill the unitary constraints would be to treat the coupled channels $\Delta N \to \Delta N$, $\Delta N \to NN$, and $NN \to NN$ near the ΔN threshold. Unfortunately experimental information on the elastic $\Delta N \to \Delta N$ channel is rather scarce. The full treatment of this coupled-channel problem is outside the scope of this work in which I have used a phenomenological description of the $\Delta N \to NN$ transition in order to evaluate the influence of the double pion photoproduction on the $\gamma D \to pp\pi^-$ reaction. This mechanism can also be considered as an exchange-current correction to the $\gamma N \to N\pi$ reaction amplitude in nuclei. The model described here is a good tool with which to look for such corrections in pion photoproduction reactions on heavier nuclei (see Ref. 8).

Finally I would like to emphasize that this mechanism leads to a small contribution to the overall cross section. It appears only when the dominant quasifree background is strongly reduced, when the pion-nucleon rescattering effects are not too strong, and when the energy of the incoming photon is high enough to create a ΔN pair. The analysis of the $\gamma D \to pp\pi^-$ reaction carried out for lower momentum, $p_2 \sim 150$ MeV/c, in Ref. 10 is not affected by this mechanism. In Ref. 7 another example is discussed where the dominant pion-nucleon rescattering amplitude is slightly modified by the double-pion-photoproduction amplitude.

[1]Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, Phys. Rev. 175, 1669 (1968).

[2]G. Gialanella *et al.*, Nuovo Cimento 63A, 892 (1969).

[3]P. Benz *et al.*, Nucl. Phys. 79B, 10 (1974).

[4]F. Carbonara *et al.*, Nuovo Cimento 36A, 219 (1976).

[5]D. Lüke *et al.*, Nuovo Cimento 53B, 235 (1968).

[6]D. Lüke and P. Söding, *Springer Tracts in Modern Physics*, edited by G. Höhler (Springer, Berlin, 1971), Vol. 59, p. 39.

[7]P. E. Argan *et al.*, preceding Letter [Phys. Rev. Lett. 41, 86 (1978)].

[8]P. E. Argan *et al.*, to be published, and in Proceedings of the International Conference on High Energy Physics and Nuclear Structure, Zurich, 29 August–2 September 1977 (unpublished).

[9]I. Blomqvist and J. M. Laget, Nucl. Phys. A280, 405 (1977).

[10]J. M. Laget, Phys. Lett. 68B, 58 (1977), and Nucl. Phys. A296, 388 (1978).

[11]R. D. Reid, Ann. Phys. (N.Y.) 50, 411 (1968).

[12]M. Brack *et al.*, Nucl. Phys. A287, 425 (1977).

[13]J. M. Laget, to be published.

[14]W. T. Nutt and C. H. Shakin, Phys. Rev. 16, 1107 (1977).

[15]W. N. Cottingham *et al.*, Phys. Rev. D 8, 800 (1973).

[16]F. Iachello *et al.*, Phys. Lett. 43B, 191 (1973).

Evidence for "Massive Transfer" in Heavy-Ion Reactions on Rare-Earth Targets

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Particle-γ coincidence experiments have been performed to study heavy-ion–induced reactions at 6–9 MeV/nucleon which lead to fast α particles. Experimental evidence is presented that the α particles are emitted in a new class of reaction called "massive transfer" which involves fusion of the remaining projectile mass. Such reactions are shown to occur with large cross section. High-spin states in the residual nuclei are populated, but side-feeding γ-ray intensities are distinctly different from those observed in (HI, $xn\gamma$) reactions [HI is heavy ion].

Heavy-ion reactions are classically divided into distinct categories based on impact parameter. Direct reactions occur in grazing collisions and result in few-nucleon transfer. Smaller impact parameters produce deep-inelastic collisions —the probability of occurrence increasing rapidly with higher projectile mass and energy. Such collisions are characterized by dissipation of a large amount of kinetic energy into internal excitations and usually include mass flow between target and projectile. The interaction times are not long enough for equilibration to occur, however, and before a compound nucleus can be formed, disruption of the system comes about. For even smaller impact parameters complete fusion does occur, followed by formation of a compound nucleus.

It has long been known that in reactions induced with heavy ions lighter than Ar an abundance of light fragments ($A \leq 4$) are produced with energies much higher than those expected from evaporation.[1-3] The angular distributions of these light particles are strongly peaked in the forward direction, suggesting that they originate in a direct interaction.[1,2] In this Letter, we present experimental evidence that these fast light particles are emitted in reactions which lead to fusion of the remaining projectile mass and that these reactions occur with rather large cross section. These "massive transfer" reactions form a new class of reactions which form a bridge between the complete fusion process and deep-inelastic and direct processes.

To study this reaction we performed a series of coincidence studies between γ rays and "direct" α particles. Several combinations of incident heavy ions and targets, as summarized in Table I, were studied to provide a sufficient amount of data from which to draw conclusions. The γ-ray spectra are used to identify the specific residual nucleus produced in the massive transfer reaction.