

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

MASTER

LA-UR -83-1397

DE83 012666

TITLE: Contributions of Double- Δ and Other Two-Nucleon Mechanisms to Pionic Pion Production on the Deuteron

AUTHOR(S): L.C. Liu, R.S. Bhalerao, and E. Piasetzky

SUBMITTED TO: Proceedings of Symposium of Delta-Nucleus Dynamics Argonne National Laboratory, Argonne, IL, May 2-4, 1983.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

Handwritten initials/signature

CONTRIBUTIONS OF DOUBLE- Δ AND OTHER TWO-NUCLEON
MECHANISMS TO PIONIC PION PRODUCTION ON THE DEUTERON

L.-C. Liu, R. S. Bhalerao, and E. Piasezky
Los Alamos National Laboratory

I. INTRODUCTION

Pion-induced single-pion production in complex nuclei is of fundamental theoretical interest since it provides a new means to study the pion field inside a nucleus. On a free nucleon, the pionic pion production threshold is at an incident pion kinetic energy of $T_{\pi} \approx 170$ MeV. In a nucleus, owing to simple kinematic reasons, the threshold for pion production is shifted downward as the mass of the nucleus increases. Consequently, we expect that the $(\pi, 2\pi)$ reaction can have appreciable cross sections even at pion energies ~ 300 MeV, an energy domain accessible at LAMPF.

We choose to first study the reaction $\pi^{-}d \rightarrow \pi^{+}\pi^{-}nn$ for the following reasons: (1) the deuteron provides the simplest nuclear environment in which pion production involving more than one nucleon can occur; (2) the internal structure of the deuteron has been extensively studied; (3) since the deuteron is a loosely bound system, the medium modification of the basic production amplitude due to the presence of the other nucleon is expected to be minimal; (4) the basic production process $\pi^{-}p \rightarrow \pi^{+}\pi^{-}nn$ has the largest cross section among all $\pi N \rightarrow \pi\pi N$ processes in the energy domain we are interested in; and, finally, (5) since the double-charge-exchange reaction (π^{-}, π^{+}) cannot occur on a deuteron, the detection of a π^{+} represents the signature of the pion production; consequently, a single-arm detection system can be used in the initial phase of experimental studies to achieve higher counting rates. (The above discussion equally applies to the mirror reaction $\pi^{+}d \rightarrow \pi^{-}\pi^{+}pp$.)

In the deuteron, the simplest pion production mechanism is the quasifree process in which the pion is produced on a single nucleon, with the second nucleon acting as a spectator (Fig. 1a). More interesting mechanisms, however, are those in which both the nucleons are actively involved, as shown in Figs. 1b to 1d. In addition, there exist higher-order two-nucleon processes involving both πN and NN rescatterings. At $T_{\pi} >$

250 MeV, there is evidence that the basic production could proceed via intermediate πN - and $\pi\pi$ -resonances, including the $\Delta(1232)$ resonance (Fig. 2).¹⁻² Considering the fact that the πN rescattering can also proceed through the formation of a $\Delta(1232)$, we then have a situation in which two $\Delta(1232)$ can be simultaneously present. Recently, G. E. Brown et al. have proposed a double- Δ model to explain certain features of pion absorption by nuclei.³ It seems useful to further examine this mechanism by use of other nuclear reactions, such as the $\pi^-d \rightarrow \pi^+\pi^-nn$ reaction. In this report, we only briefly describe our calculations of the diagrams shown in Figs. 1a and 1b. We have also omitted the distortion of the incoming pion wave. This approximation should not affect our conclusion concerning the relative importance of the two diagrams studied.

II. CALCULATIONS

In the plane-wave Born approximation of Fig. 1a, the double differential cross section in the c.m. system corresponding to detecting the π^+ at a given energy and a given angle can be written as:

$$\frac{d^2\sigma}{d\omega_1 d\cos\theta_1} = K \int \frac{d^3\vec{p}_4}{(E_4/M)} J \sum_{\nu'\nu} \left(\frac{d^2\sigma}{d\omega_1^* d\cos\theta_1^*} \right)_{\nu'\nu} \times \sum_{\lambda\mu} |\langle \mu \nu | \phi_{1\lambda}(\vec{Q}) \rangle|^2 \quad (1)$$

where the subscripts 1 and 4 refer, respectively, to π^+ and the spectator neutron, and K is a kinematical factor. The quantities denoted with $*$ are defined in the center-of-mass frame of the π^-p system, and $J \equiv (d\omega_1/d\omega_1^*) \times (d\cos\theta_1/d\cos\theta_1^*)$ is the Jacobian of transformation. The μ and ν' are the spin projections of the neutrons and the ν and λ are, respectively, the spin projections of the proton and the deuteron. ϕ is the wave function of the deuteron, and \vec{Q} is the momentum variable. In the nonrelativistic limit, $\vec{Q} = \frac{1}{2}\vec{k}_0 + \vec{p}_4$, with \vec{k}_0 being the c.m. momentum in the πd system. Calculated cross sections shown in this report are based on the deuteron

wave function of Ref. 4. Use of other deuteron wave functions has led to essentially identical results.

We have used experimental $d^2\sigma/d\omega^*d\cos\theta^*$ of the reaction $\pi^-p \rightarrow \pi^+\pi^-nn$ as the input to our calculations and have parameterized them according to:

$$d^2\sigma/d\omega^* d\cos\theta^* = \left(\sum_{ij} A_{ij} (\bar{W})^i (\cos\theta^*)^j \right) \times \text{Ph}_3(\bar{W}, \cos\theta^*), \quad (i, j=0, 1, 2). \quad (2)$$

where Ph_3 is the three-body phase space integrated over the other variables and \bar{W} is the invariant mass of the π^-p system. Since the experimental double differential cross sections are averaged over the spin of the nucleons, the use of Eq. 2 also requires the introduction of an appropriate spin average in Eq. 1. When both the diagrams of Figs. 1a and 1b are included, the differential cross sections are given by

$$\begin{aligned} \frac{d^2\sigma}{d\omega_1 d\cos\theta_1} = & K' \int \frac{d\vec{p}_4}{(E_4/M)} \frac{d\vec{p}_3}{(E_3/M)} \frac{d\vec{k}_2}{2\omega_2} k_1 d\phi_1 \\ & \times \delta(\omega_1 + \omega_2 + E_3 + E_4 - W) \delta(\vec{k}_1 + \vec{k}_2 + \vec{p}_3 + \vec{p}_4) \\ & \times \sum_{\nu'\mu'\lambda} \left| \int \frac{d^2\vec{p}'_4}{(E'_4/M)} \sum_{\nu\mu} M_{\nu'\nu}(\omega'_1, \cos\theta'_1) \{ \delta(\vec{p}'_4 - \vec{p}'_4) \delta_{\mu'\mu} \right. \\ & \left. + [(\omega_1 + E_4 - E'_4)^2 - \omega_1'^2 + i\epsilon]^{-1} T_{\mu'\mu}(1, 4 + i, 4') \} \langle \nu\mu | \phi_{1\lambda}(\vec{Q}') \rangle \right|^2. \quad (3) \end{aligned}$$

Here, we use $\omega_j = (\vec{k}_j^2 + M_\pi^2)^{1/2}$, ($j = 1, 2$), and $E_j = (\vec{p}_j^2 + M^2)^{1/2}$, ($j = 3, 4$) to denote, respectively, the pion and nucleon energies in the final state. W is the total energy of the πd system and is given by $W = (\vec{k}_0^2 + M_\pi^2)^{1/2} + (\vec{k}_0^2 + M_d^2)^{1/2}$. Further, $T_{\mu'\mu}$ denotes the π^+n scattering amplitude. The momentum variable of the deuteron wave function is $\vec{Q}' = \frac{1}{2} \vec{k}_0 + \vec{p}'_4$. One can show that this expression reduces to Eq. 1 when the rescattering term is absent. An exact evaluation of Eq. 3 requires the knowledge of the phase of the production amplitude $M_{\nu'\nu}$. Since we are using experimental cross sections to infer M , we have neglected the phase of $M_{\nu'\nu}$ and carried out the spin average over $M_{\nu'\nu}$. As a further simplification, we have calculated the rescattering using on-shell geometry. This approximation might be justified by the fact that the average separation between the two nucleons in the deuteron is large compared to the range of πN scattering.

Results of our calculations are presented in Fig. 3. The solid curves represent cross sections obtained from a four-body phase-space calculation, assuming $M_{\nu, \nu} \times \phi = \text{constant}$. The other four curves are based on Eqs. 1 and 2, the quasifree model, and correspond to the cross sections calculated with $\cos\theta_1 = 0.75$ (the dashed curve), 0.25 (the dot-dashed curve), -0.25 (the dotted curve), and -0.75 (the crossed curve), respectively. We note that the phase-space result is independent of $\cos\theta_1$. The solid curve has been normalized to yield the same total production cross section as obtained with the quasifree model. With respect to the phase-space calculation, use of the quasifree model shifts the maximum of the cross sections to a higher value of T_1 , the kinetic energy of π^+ in the four-body c.m. system. The shift is bigger for smaller values of θ_{π^+} (denoted θ_1).

The differential cross sections predicted by the quasifree model at $T_{\pi^+} = 256$ MeV agree fairly well with the preliminary data obtained at LAMPF (Exp. 783, LAMPF-MIT-Tel-Aviv collaboration). The inclusion of π^+n rescattering increases calculated cross sections. The increase is bigger for smaller values of $\cos\theta_1$. For $\cos\theta_1 = +0.75$, calculated cross sections are, respectively, increased by about 4 and 6% at 256 and 331 MeV. For $\cos\theta_1 = -0.75$, the π^+n rescattering increases cross sections in the region where there is a maximum by about 20 and 30% at 256 and 331 MeV, respectively. Theoretical results based on the use of microscopic theories for the basic $\pi N \rightarrow \pi\pi N$ process and on full calculations of all the diagrams shown in Fig. 1 will be given elsewhere.

Since the average energy for πN rescattering at 256 and 331 MeV is equivalent to free pion-nucleon scattering at pion energies between 60 and 100 MeV, which are well below the $\Delta(1232)$ resonance energy, it seems useful to study the $\pi^-d \rightarrow \pi^+\pi^-nn$ reaction at higher energies to look for a more clear signature of the double- Δ mechanism.

This work is supported by U.S.D.O.E., Division of Nuclear Physics.

REFERENCES

1. R. A. Arndt, J. B. Cammarata, Y. N. Goradia, R. H. Hackman, V. L. Teplitz, D. A. Dicus, R. Aaron, and R. S. Longacre, Phys. Rev. D 20, 651 (1979).
2. D. M. Manley, Ph.D. Thesis, University of Wyoming, unpublished, Los Alamos National Laboratory Report LA-9101-T, Nov. 1981.
3. G. E. Brown, H. Toki, W. Weise, and A. Wirzba, Phys. Lett. 118B, 39 (1982).
4. R. Reid, Ann. Phys. (NY) 50,411 (1968).

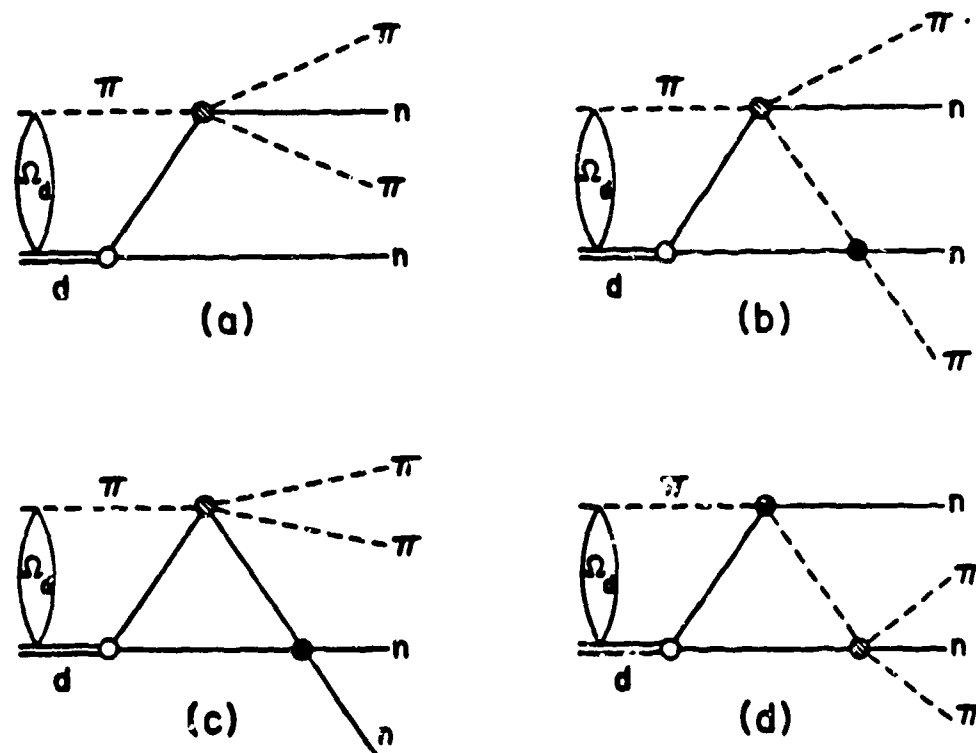


Fig. 1. Diagrams contributing to the reaction $\pi^- d \rightarrow \pi^+ \pi^- n n$. (a) Born approximation; (b) π production followed by πN rescattering; (c) π production followed by NN rescattering; and (d) deuteron breakup followed by π production. In all diagrams, Ω_d is the wave matrix for the distortion of pion wave, the open circle is the $d\pi n$ vertex, the shaded circle is the production amplitude, and the solid circle is the πN or NN scattering amplitude.

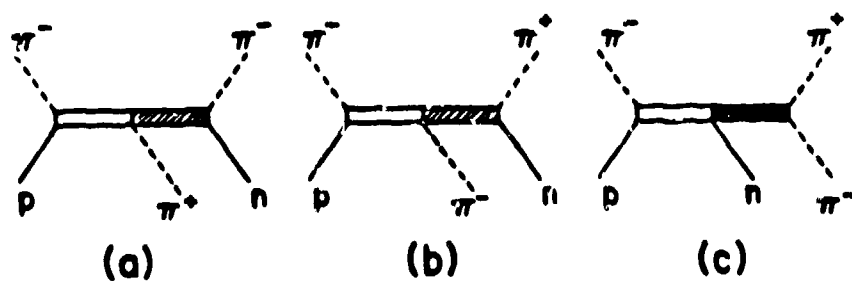


Fig. 2. Pion-induced single-pion production on a nucleon (isobar model). Each of these diagrams is further supplemented by diagrams obtained from crossing the pion lines.

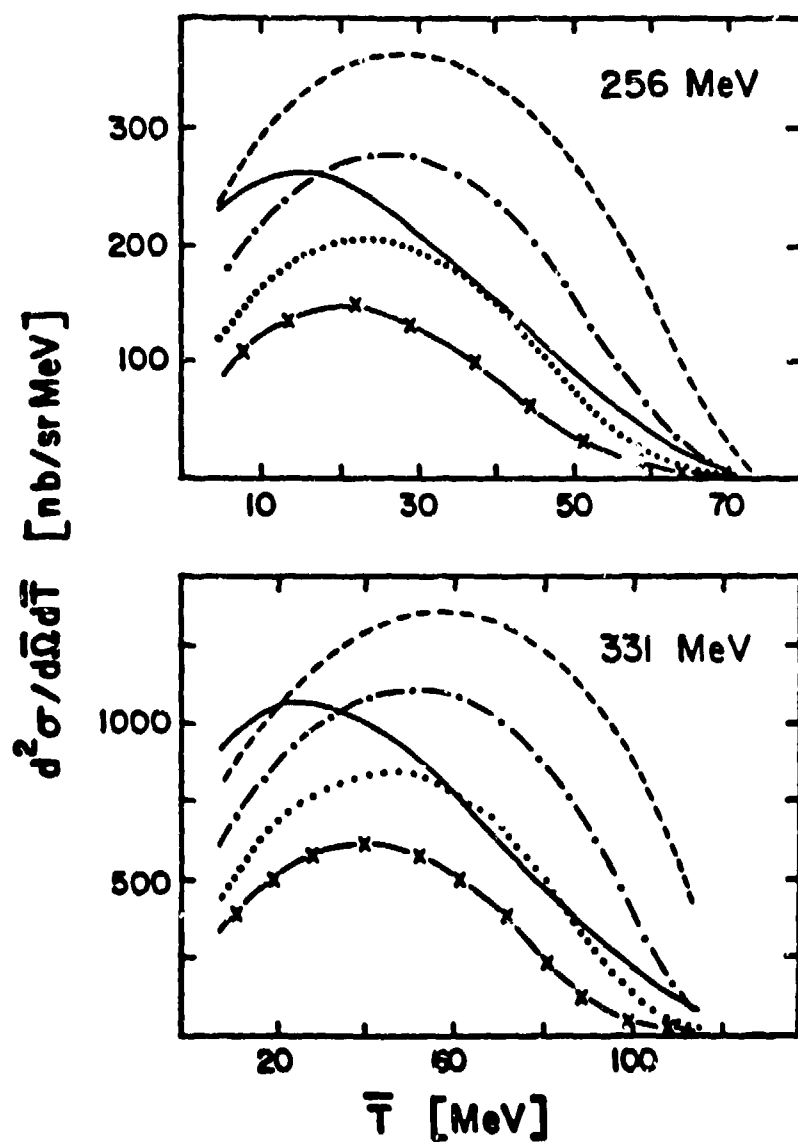


Fig. 3. Double-differential cross section for the reaction $\pi^-d + \pi^+\pi^-nn$ at $T_{\pi^-} = 256$ and 331 MeV. The quantities \bar{T} and $\bar{\Omega}$ denote, respectively, the kinetic energy and the solid angle of π^+ in the c.m. frame of the four-body system. The meaning of the curves is given in the text.