Pion-Induced Pion Production on the Deuteron

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Doubly differential cross sections were measured for pion production in the reaction $\pi^- d \to \pi^+\pi^- nn$ at 256 and 331 MeV and in $\pi^+ d \to \pi^-\pi^+ pp$ at 256 MeV. At each incident energy observations were made at 35 to 40 points distributed uniformly over the center-of-momentum phase space of the produced pion. Comparison of these measurements with the cross sections for $\pi^- p \to \pi^+\pi^- n$ suggests that they are consistent with the dominance of quasifree production on a single nucleon. Upper limits for production of bound $\pi^- nn$ and $\pi^+ pp$ systems were measured.

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Pion-induced pion production $(\pi, 2\pi)$ has been studied systematically on the proton,[1] but there is virtually no information about this process in nuclei. The interest in this reaction in heavier systems lies with the possible existence of mechanisms in which more than one nucleon is actively involved. The simplest of these systems is the deuteron. The reactions

$$\pi^- d \to \pi^+\pi^- nn \text{ and } \pi^+ d \to \pi^-\pi^+ pp$$

can be studied and compared with $\pi^- p \to \pi^+\pi^- n$ to search for two-nucleon mechanisms.

One two-nucleon mechanism for $(\pi, 2\pi)$ was proposed by Brown *et al.*[2] who predicted the existence of a strong $\Delta N \to \Delta\Delta$ transition in systems of two or more nucleons on the basis of the SU(4) quark model. Subsequent decay of the two Δ's contributes to the $(\pi, 2\pi)$ reaction. The deuteron, as the simplest system in which a $\Delta\Delta$ state may occur, is an interesting case to study. However, a $\Delta\Delta$ system formed in $\pi^\pm d$ reactions must be in a $T=1$ state, whereas the $T=2$ configuration is preferred by a factor of 3 for the $\Delta N \to \Delta\Delta$ transition.

The $\pi^- nn$ or the $\pi^+ pp$ component of the final state has $T=2$. If the NN system is formed at low momentum it is likely to be in a $^1S_0$ state with $T=1$. The pion may then be attracted to it through the P_{33} interaction to form a state that may be considered an off-shell ΔN. In heavier nuclei these $T=2$ ΔN states can be doorways to the formation of $T=2$ $\Delta\Delta$ states. Since a $T=2$ ΔN state cannot decay by either the strong or the electromagnetic interaction it may appear in the reactions studied here as a narrow resonance or even as a bound state. If it existed, an unbound resonance would appear as an enhancement of the production cross section while a bound state would appear as a peak at an energy beyond the upper edge of the phase space allowed for production. Garcilazo[3] has recently shown that calculations predict the existence of a bound state with certain parametrizations of the πN and NN interactions. However, the uncertainties in our knowledge of these parametrizations and, in particular, of the πN effective range leave ample room to doubt its existence. Observation of this state and measurement of the cross section (or even an upper limit on the cross section) for its formation is therefore of interest.

We report on an experimental study of the reactions $\pi^\mp d \to \pi^\pm\pi^\mp NN$ that was performed at the high-energy pion channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). The doubly differential cross section $d^2\sigma/d\Omega\, dT$ for the production of pions with charge opposite to that of the incident beam was measured at uniformly distributed locations in $\overline{T}$-cos$\overline{\theta}$ phase space, where $\overline{T}$ and $\overline{\theta}$ are the kinetic energy and angle of the outgoing pion in the center-of-mass system of the incident pion and deuteron. Since double charge exchange is impossible on the deuteron, this method unambiguously identifies pion production. Measurements were made with π^+ and π^- beams at an incident kinetic energy of 256 MeV and with a π^- beam at 331 MeV. The momentum spread of the beams was $\Delta p/p = 4\%$ and their intensities were approximately $2\times10^8\ \pi^-/\mathrm{s}$ and $10^9\ \pi^+/\mathrm{s}$.

The outgoing particles were detected by a 180° double-focusing magnetic spectrometer[1,4–6] with a solid angle of 15 msr and momentum acceptance of $\pm4.8\%$. The detector system consisted of a multiwire proportional chamber between the two dipole magnets of the spectrometer, a pair of multiwire proportional chambers immediately behind the focal plane, a 1.6-mm-thick plastic scintillation detector, a fluorocarbon (FC-88) threshold Čerenkov counter, and lastly, an Aerogel ($n = 1.055$) Čerenkov counter. A quadrupole coincidence among signals from the three wire-chamber delay lines and the scintillator triggered the recording of an event. The last two wire chambers established the trajectory of a particle as it crossed the focal plane. For events which corresponded to an allowable trajectory, pulse heights from the scintillator and Čerenkov detectors and the time of flight through the second bending magnetic discriminated against electrons or, when set for positive charge, positrons, protons, and other light nuclei. Corrections for pions decaying in the relatively short 3.5-m flight path and for muons that were recorded as good events were calculated with the Monte Carlo simulaton DECAY TURTLE.[6] A cylindrical target flask 2.5 cm in diameter, which was concentrically mounted on the axis of rotation of the spectrometer, contained either liquid deuterium (99.83% deuterium) or liquid hydrogen. Background from the 50-μm Mylar walls was observed with the flask empty. The incident pion flux was measured with an ionization chamber upstream as well as with a scattering monitor downstream from the spectrometer.

The measured pion-production cross sections were normalized to πp elastic scattering. At each incident energy, relative πp elastic cross sections were measured at several angles and the angular distribution was normalized to fit the "known cross sections" with a scale factor that calibrated the system as a whole. Below 300 MeV, known cross sections were derived from the phase-shift analysis of Carter, Bugg, and Carter[7] using the routine SCATPI.[8] Above this energy, they were interpolated directly from the measurements.[9] The interpolation procedure is described in detail in Ref. 5 and is the same procedure used to normalize the $\pi^-p\to\pi^+\pi^-n$ cross sections of Ref. 1.

Figure 1 shows the doubly differential cross sections for the reaction $\pi^-d\to\pi^+\pi^-nn$ at 256 and 331 MeV. At 256 MeV the measured cross sections for the reaction $\pi^+d\to\pi^-\pi^+pp$ are equal to those for the reaction $\pi^-d\to\pi^+\pi^-nn$ within the experimental uncertainties. The errors shown in the figure represent the combination of statistical uncertainty and those systematic uncertainties that depend on the outgoing momentum. Overall normalization is uncertain by a further 4%.

These data are compared with two simple models of the reaction. The solid curves in Fig. 1 represent the distribution of events in four-body phase space, normalized so that the integral of the distribution over energy and angle will equal the integrated reaction cross section determined from the data. The dashed curves are the predictions of a calculation,[10] in plane-wave Born approximation, of quasifree pion production on one nucleon using phenomenological on-shell amplitudes deduced from the $\pi^-p\to\pi^+\pi^-n$ data[11] in the energy range from 203 to 450 MeV. Once the production amplitude is chosen, the quasifree calculation involves no other free parameters. It is in surprisingly good agreement with the general features of the data, although some discrepancies do exist. At 256 MeV the quasifree calculation reproduces the shape of the spectra very well, but the absolute value of the cross section is 20% below the measured result. The dotted curve in Fig. 1 is the quasifree calculation normalized by the ratio of the measured and calculated integrated cross sections. At 331 MeV both the shape and the integrated reaction cross section obtained from the quasifree calculation agree with the measurement within the experimental uncertainty.

The measured doubly differential cross sections were integrated over the energy and angle of the produced pion to determine an integrated reaction cross section. To estimate the contribution from the unobserved kinematic range we assumed the form of the cross section given by the plane-wave Born approximation and assigned a 25% uncertainty to the contribution from the extrapolated region. The integrated reaction cross sections for $\pi^-d\to\pi^+\pi^-nn$ are $160\pm10\ \mu$b at 256 MeV and $1000\pm100\ \mu$b at 331 MeV. The corresponding cross sections for $\pi^-p\to\pi^+\pi^-n$ are $166\pm6\ \mu$b

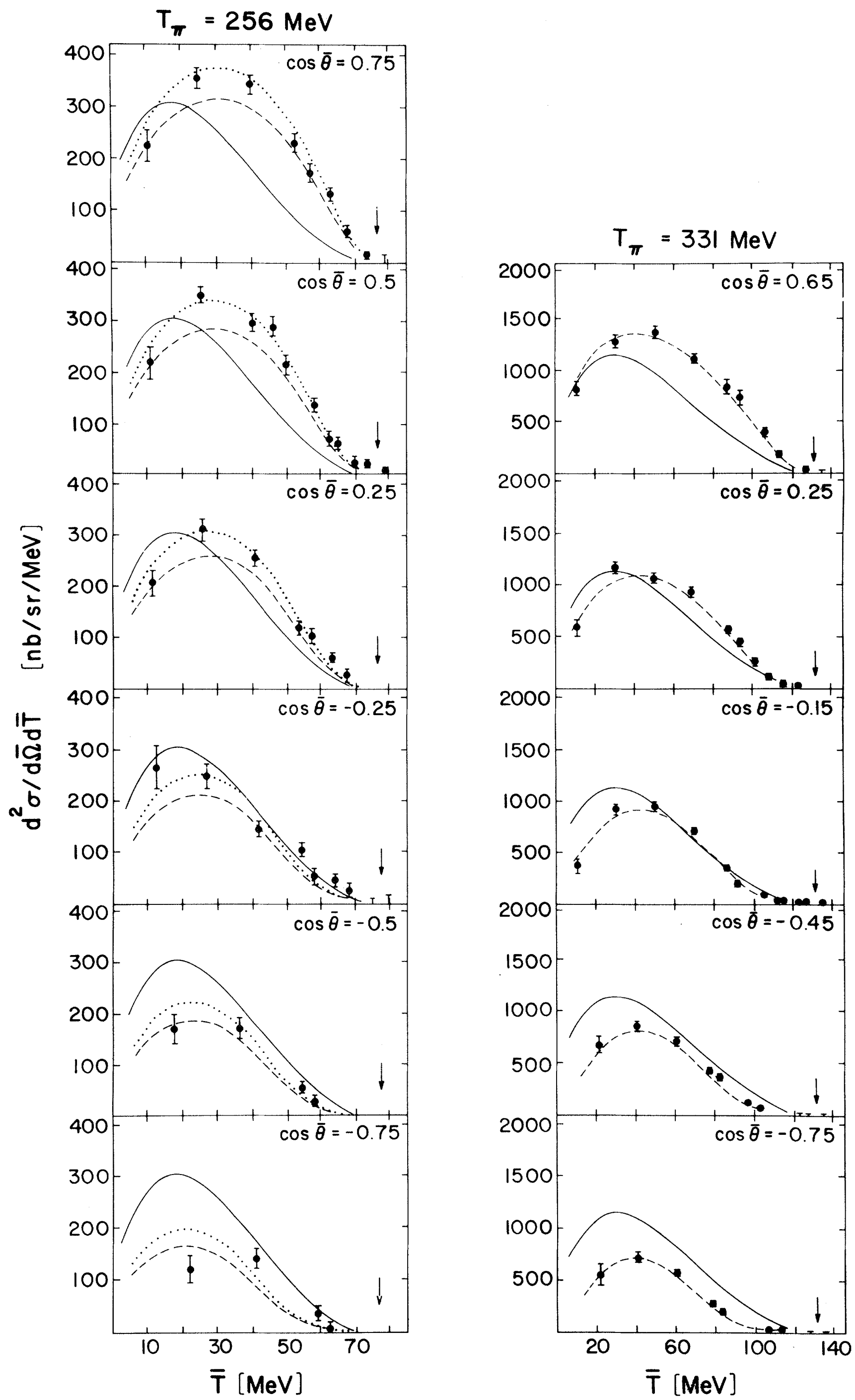

FIG. 1. Doubly differential cross section for the reaction $\pi^- d \rightarrow \pi^+\pi^- nn$ at 256 and 331 MeV. $\bar{T}$ and $\bar{\theta}$ are the outgoing π^+ kinetic energy and angle in the center-of-mass system. The arrows mark the energy corresponding to the two-body $\pi(\pi NN)$ production with zero binding energy for the πNN system. The solid curves represent four-body phase space normalized to the data. The dashed and dotted lines are quasifree calculations in plane-wave Born approximation (see text).

and 1160 ± 50 μb at 256 and 331 MeV, respectively.[1] At this level of accuracy there is no discernible difference between the integrated reaction cross sections for pion-induced pion production on the deuteron and the proton. This, coupled with the similarity between observation and the cross sections predicted by the simple quasifree calculation, indicates that two-nucleon effects contribute little to pion production on the deuteron. It will be interesting to compare this result with observation of the same reaction in heavier nuclei where two-nucleon effects should be more prevalent.

In Fig. 1 the arrows mark the energy corresponding to two-body $\pi(\pi NN)$ production with zero binding energy for the πNN system. The low cross sections measured at the high-energy edge of the four-body phase space show no evidence for the production of a weakly bound πNN system. We can set upper limits on the cross section for formation of bound $\pi^- nn$ and $\pi^+ pp$ systems in the two reactions, with the results presented in Table I. These upper limits were determined predominantly by the statistics of the measurements and the energy resolution of the system. The energy resolution, defined mainly by the beam, was about 12, 10, and 8.5 MeV for the 331-MeV π^-, 256-MeV π^-, and 256-MeV π^+ measurements, respectively.

In summary, we have measured pion-induced pion production on the deuteron and compared it with pion production on the proton. The total cross sections for $\pi^- d \rightarrow \pi^+\pi^- nn$ and $\pi^- p \rightarrow \pi^+\pi^- n$ are found to be equal at both 256 and 331 MeV. The doubly differential cross sections for $\pi^+ d \rightarrow \pi^-\pi^+ pp$ and $\pi^- d \rightarrow \pi^-\pi^+ nn$ are found to be equal at 256 MeV. A plane-wave Born-approximation calculation fits the shape of the measured doubly differential cross section throughout the observed angular range at both 256 and 331 MeV. Its normalization is 20% low at 256 MeV, but correct at 331 MeV. At both energies the shape of the four-body phase space resembles the data at backward angles, but falls below the high-energy part of the cross section at forward angles. The dominant process seen in these data appears to be quasifree production on a single nucleon. This result invites explanation by a detailed microscopic theory that treats both the reaction mechanism and final-state interactions, and experiments to search for two-nucleon mechanisms in pion production on heavier nuclei.

TABLE I. Upper limits for formation of bound $\pi^- nn$ and $\pi^+ pp$ systems in the reactions $d(\pi^-,\pi^+)\pi^- nn$ and $d(\pi^+,\pi^-)\pi^+ pp$. Over narrower angular ranges these upper limits are two to three times smaller.

T_π (MeV)	Reaction (system)	Binding energy range (MeV)	Angular range ($\bar{\theta}$) (deg)	Upper limit (nb/sr)
256	$d(\pi^+,\pi^-)$ $(\pi^+ pp)$	0–6	40°–105°	200
256	$d(\pi^-,\pi^+)$ $(\pi^- nn)$	0–6	40°–105°	300
331	$d(\pi^-,\pi^+)$ $(\pi^- nn)$	0–10	50°–140°	500
331	$d(\pi^-,\pi^+)$ $(\pi^- nn)$	0–20	99°–101°	500

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[11]The data base from which the phenomenological amplitude is derived includes the results of Refs. 1 and 5 in the energy range from 203 to 358 MeV as well as a new measurement we have performed at 450 MeV. The addition of these high-energy data improved the agreement between the quasifree calculation and the measurement at 331 MeV as can be seen by comparing the curve in Fig. 1 with the previous calculation in Ref. 10.