Isospin Dependence of Pion Absorption on Nucleon Pairs at $T_\pi = 65$ MeV

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Angular distributions of differential cross sections were measured for the first time for pion absorption on a $T=1$, $S=0$ nucleon pair and for absorption on a $T=0$, $S=1$ pair in the ^{3}He nucleus. A large isospin dependence is observed in the differential cross sections. The ratio of cross sections $\sigma(^3\mathrm{He}(\pi^+, 2p))/\sigma(^3\mathrm{He}(\pi^-, pn))$ is 15.2 ± 1.2. The results show evidence of an isoscalar component of the final state in the reaction $^3\mathrm{He}(\pi^-, pn)n$, which cannot be mediated by Δ resonance formation.

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A fundamental process of pion absorption is the two-body mechanism $\pi + NN \rightarrow NN$. To date, mainly two-body absorption on the deuteron ($T=0$, $S=1$) was studied.[1,2] Studies of pion absorption on a $T=1$, $S=0$ nucleon pair can give information on states not accessible through absorption on the deuteron. The quantum numbers involved in pion absorption on $T=0$, $S=1$ and $T=1$, $S=0$ nucleon pairs are shown in Table I for absorption through *s*- and *p*-wave pions. At energies near the (3,3) resonance pion absorption on a $T=0$, $S=1$ pair is dominated[2-4] by the $\pi NN \rightarrow \Delta N \rightarrow NN$ transition where the intermediate ΔN system is in a 2^+ state with relative angular momentum $L_{\Delta N}=0$. For absorption on $T=1$, $S=0$ pairs, intermediate ΔN states cannot have $L_{\Delta N}=0$,

TABLE I. Quantum numbers involved in pion absorption on nucleon pairs. The subscripts *i*, ΔN, and *f* refer to the initial nucleon pair, the ΔN intermediate system, and the final nucleon pairs. The orbital angular momentum of the π-$2N$ system is denoted by $l(\pi\text{-}2N)$.

J_i^π, T_i $L_i=0$	$l(\pi\text{-}2N)$	$J_{\Delta N}^\pi$; $L_{\Delta N}$ $T_{\Delta N}=1$	J_f^π; L_f; T_f: $^{(2S+1)}L_J$
$1^+, 0$	0	$1^-;1$	1^-; 1; 1: $^3P_1$
	1	$0^+;2$	0^+; 0; 1: $^1S_0$
		$2^+;0,2$	2^+; 2; 1: $^1D_2$
$0^+, 1$	0	$0^-;1$	0^-; 1; 1: $^3P_0$
	1	No Δ	1^+; 0; 0: $^3S_1$
			1^+; 2; 0: $^3D_1$

and therefore there will be increased sensitivity to other processes involved in pion production. For example, recent calculations[5] suggested that an $N^*(P_{11})$ isobar could have a significant effect for p-wave absorption on a $S=0$ pair, since an intermediate N^*N state with $L_{N^*N}=0$ could be formed. Or following other calculations,[6] there could be significant contributions from s- and d-wave absorption with $L_{\Delta N}\neq 0$ intermediate states.

Pion absorption on a $T=1$, $S=0$ nucleon pair can be studied by use of the reaction $^3\mathrm{He}(\pi^-,pn)n$ where proton-neutron coincidence measurements are made, selecting the kinematic conditions to minimize the energy transferred to the undetected neutron. In addition to bearing directly on the elementary two-body absorption process, absorption data on nucleon pairs are essential ingredients in attempts to understand pion-nucleus interactions. A light system such as ^{3}He is important in order to maximize the likelihood that the detected nucleons come directly from the elementary absorption process without undergoing final-state interactions. Calculations of Lee and Ohta[7] show that the effect of the three-body absorption is small at the conditions where the energy of the undetected nucleon is minimized. Pion absorption in ^{3}He has been studied by Gotta *et al.*[8] for stopped π^-, by Ashery *et al.*[3] at $T_\pi = 165$ MeV, and by Backenstoss *et al.*[9] at $T_\pi=120$ MeV. Absolute cross sections and angular distributions were not measured in these previous experiments.[3,9] In this Letter, for the first time, differential cross sections are given for pion absorption on a $T=1$, $S=0$ nucleon pair, as well as on a p-n pair in ^{3}He.

We studied the reactions $^3\mathrm{He}(\pi^+,2p)p$ and $^3\mathrm{He}(\pi^-,pn)n$ at $T_\pi=65$ MeV at the TRIUMF accelerator by coincidence measurements of the outgoing nucleons. Protons were detected with three ΔE-E NaI(Tl) telescopes. Coincident neutrons or protons were detected with a 1-m^2 array consisting of two layers of plastic scintillators, each containing seven bars of 15-cm thickness, located 225 cm from the target. Timing information from each scintillator determined the location of the detected particle and its energy by time of flight. A scintillator in front of the array served to discriminate between charged and neutral particles. A liquid-^{3}He target of thickness of 145 mg/cm^2 (including 15-mg/cm^2 ^{4}He in the windows) was used.[10] The ^{3}He target thickness was determined by measuring the $^3\mathrm{He}(\pi^-,n)d$ reaction yield and comparing with known cross sections.[11] Background measurements were taken with ^{3}He removed from the target. Measurements with a ^{4}He target gave corrections of about 20% for $(\pi^+,2p)$ and 12% for (π^-,pn) data. The neutron detection efficiency of the array (approximately 30% with the threshold set at 3 MeV) was calculated with a code originally written by Kurz and modified by Ullrich, Gotta, and Maiers.[12] The uncertainty in the absolute values of the cross sections, arising mainly from uncertainties in the target thickness and ^{4}He contribution, is about 20%. Measurements were taken for protons at six NaI(Tl) detection angles while the array was positioned at the angle corresponding to the free $d(\pi^+,pp)$ kinematics (conjugate angle). Measurements at nonconjugate geometry were taken simultaneously.

Two-dimensional kinematic plots of the events (with respect to the energies measured in the two detectors) are used to reduce backgrounds by selecting events in the allowed region of three-body kinematics. In Fig. 1 we show proton energy spectra at 120° in the NaI detector. In both spectra we observe a peak at the energy corresponding to two-

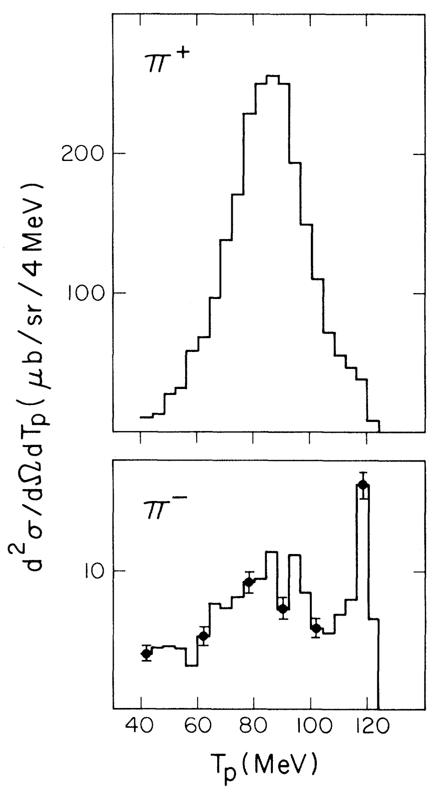

FIG. 1. Spectrum of protons at 120° in coincidence with protons (π^+) or neutrons (π^-) at $-45°$ from the reactions $^3\mathrm{He}(\pi^+,2p)p$ and $^3\mathrm{He}(\pi^-,pn)n$ for $T_\pi=65$ MeV. The spectrum in the case of π^+ has been multiplied by 0.80, and in the case of π^- by 0.88 to account for the ^{4}He present in the target windows.

nucleon absorption. A second peak is seen [more clearly for the (π^-,pn) reaction] at the high-energy edge of the $3N$ phase space, where two nucleons having approximately the same vector momentum recoil against the third. We obtained the angular correlation for (π^+,pp) between the proton in the NaI telescope and the coincident proton in the scintillation array. After unfolding the broadening due to finite detector sizes, this correlation shows a roughly Gaussian peak centered around the conjugate angle with a full width at half maximum of about 12°. This relatively narrow correlation is consistent with the picture of absorption proceeding through an intermediate state with $L_{\Delta N}=0$, since the Δ then effectively pairs off only with a nucleon of equal momentum moving parallel to itself. For (π^-,pn) the data have larger statistical uncertainties since the lower cross section, lower π^- fluxes, and the need to detect neutrons result in a detection rate three orders of magnitude smaller than for $(\pi^+,2p)$. The same angular correlation was assumed for the (π^-,pn) data where the measured angular correlation was consistent with the (π^+,pp) correlation. Measurements done in nonconjugate geometry were used to estimate the three-nucleon absorption background for $(\pi^+,2p)$. The three-body $(3N)$ part of the absorption process is assumed to be distributed over the outgoing particle's angles and energies according to the phase-space factor. The angular correlations were fitted to a two-dimensional Gaussian and $3N$ phase-space background. The fraction of the $2N$ cross section within the limits of the scintillation array was about 80%, as determined by this fitting procedure. The measured $2N$ yield in the NaI energy spectrum is then corrected for the missing acceptance. In principle the $2N$ and $3N$ reaction amplitudes add coherently. However, since experimentally there are no means of separating these two processes at the conjugate angle we have treated the $3N$ portion of the spectrum as an incoherent background in obtaining the $2N$ piece.

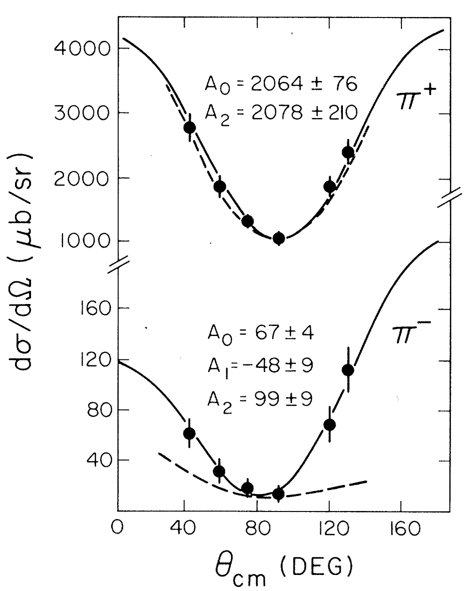

FIG. 2. Differential cross section for the two-body portion of the reactions $^3He(\pi^+,2p)p$ and $^3He(\pi^-,pn)n$ at $T_\pi=65$ MeV. The solid lines are Legendre polynomial fits with coefficients A_0, A_1, A_2 given in microbarns per steradian. The dashed curves are predictions by Silbar and Piasetzky (Ref. 5).

The angular distributions deduced for the $2N$ part of the two reactions are shown in Fig. 2. The cross sections are given in the πd center-of-mass system. The errors include statistical and background subtraction uncertainties, and angle-dependent systematic uncertainties. For (π^+,pp) the shape of this angular distribution is very similar to that[1] of the reaction $d(\pi^+,pp)$. This is reflected in a value consistent with zero for the A_1 term. For (π^-,pn) the angular distribution shows significant asymmetry about 90°, which is a signature of mixture of even and odd partial waves, indicating that part of this reaction proceeds through non-Δ absorption (see Table I).

The integrated cross sections deduced from the Legendre polynomial fits are $\sigma(\pi^+,pp)=12.9 \pm 0.6$ mb and $\sigma(\pi^-,pn)=0.84 \pm 0.05$ mb. In addition there is an absolute uncertainty of 20% common to both cross sections. Note that because of the symmetry in the final state, $\sigma(\pi^+,pp)$ is obtained from an integration over a solid angle of 2π. The $^3He(\pi^+,pp)$ cross section is larger than the $d(\pi^+,pp)$ cross section[1] by a factor of 1.74 ± 0.36. This is in qualitative agreement with the observation[13] made in single-arm proton measurements and expectations assuming that ^3He has 1.5 pn pairs with the deuteron quantum numbers. The magnitude of the cross section is not significantly affected by the higher density of ^3He; consistent with the prediction[14] that the short-range behavior of the $S=1$ pairs in ^3He and the deuteron are similar.

We compare our data in Fig. 2 with angular distributions calculated by Silbar and Piasetzky.[5] The calculations are normalized to the (π^+,pp) data. For (π^-,pn) the calculations do not reproduce the shape of the angular distribution.

We find that the ratio of cross sections between (π^+,pp) and (π^-,pn) reactions $R=15.3 \pm 1.2$ is smaller than the average value at $T_\pi=165$ MeV. Compared with the rise[1] in the $d(\pi^+,pp)$ cross sec-

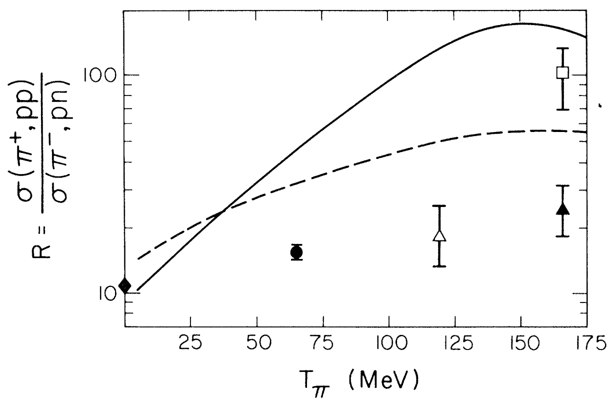

FIG. 3. Ratio $R=\sigma(\pi^+,pp)/\sigma(\pi^-,pn)$ for pion absorption on ^{3}He for various energies. The data points are lozenge, Ref. 8, circle, present experiment, square, Ref. 3 (average 55° and 75°), open triangle, Ref. 9 (average 54° and 77°), closed triangle, Ref. 9 (54°). The lines are the results of theoretical calculations: solid line, Ref. 5; dashed line, Ref. 6.

tion from 65 to 165 MeV, the $^3\mathrm{He}(\pi^-,pn)$ cross section is flat or even decreasing over the same energy region. The energy dependence will be determined when complete angular distribution measurements at 165 MeV become available.[15] This fact indicates that the Δ resonance is not the dominant channel for the π^--induced reaction. Theoretical calculations[5,6] for this ratio, together with the present and previous experimental data, are given in Fig. 3 as a function of pion energy.

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