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Isospin Dependence of Pion Absorption on ^{3}He

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It is shown that the strong isospin dependence observed in pion absorption on ^{3}He can be described by the two-body mechanism $\pi NN \rightleftarrows \Delta N \rightleftarrows NN$. The effect of the three-body mechanism is also calculated but found to be negligibly small. The $\Delta N \rightleftarrows NN$ dynamics consistently determined from NN inelasticities is shown to be essential to understand the isospin dependence.

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It is now well recognized that unless pion absorption by nuclei is understood on a microscopic level, we will not be able to reach an internally consistent description of pion-nucleus interactions. Pion absorption on the deuteron has been studied extensively and can be described very well with the Δ-excitation mechanism $\pi NN \to \Delta N \to NN$. Because of the restriction of spin and isospin of the deuteron wave function, the $\pi^+ d$ process only probes very limited $\Delta N \rightleftarrows NN$ dynamics. For a complete microscopic understanding of pion abosrption it is necessary to investigate heavier nuclei in which a pair of nucleons with different spin and isospin is accessible.

Recent coincidence measurements (π^+, pp) and (π^-, pn) by Ashery *et al.*[1] have shown that the two-body $\pi NN \to N\Delta \to NN$ process for a $T=1$ pair of nucleons in He target nuclei is strongly suppressed and its strength relative to a $T=0$ pair of nucleons does not follow a simple isospin argument. Since nucleons in He are predominantly in the relative s states, the intermediate ΔN in the $^5S_2$ state, which dominates absorption for a $T=0$ nucleon pair, is forbidden for a $T=1$ pair (see Table I of Ref. 1). It is clear that we need a sufficiently detailed $\Delta N \rightleftarrows NN$ dynamics to explain these important data.

In this Letter we report the results of a calculation of the (π^+,pp) and (π^-,pn) reactions on ^{3}He based on the model of Betz and Lee (BL)[2] for π, N, and Δ. We show that the relative cross sections measured by Ashery *et al.* can be understood successfully from the $\pi NN \rightleftharpoons \Delta N \rightleftharpoons NN$ dynamics *determined from the πN and NN scattering data.* It is found that no additional absorption mechanisms are necessary.

The BL model Hamiltonian can be summarized as

$$H = H_0 + V_0 + V', \tag{1}$$

where H_0 is the free Hamiltonian for π, N, and Δ; V_0 is the $\Delta N \rightleftharpoons NN$ and $NN \rightleftharpoons NN$ potential; and V' is the $\pi N \rightleftharpoons \Delta$ interaction. (BL also included a small πN potential but we suppress it here.) The strategy of BL is to determine the interactions V_0 and V' by fitting experimental phase shifts of NN scattering up to about 1 GeV and πN scattering up to 300 MeV. For the present study of pion absorption, it is important to note that by fitting the NN inelasticities given by the phase-shift analysis, the essential dynamics of the $\pi NN \rightleftharpoons \Delta N \rightleftharpoons NN$ process is incorporated in the model. To be specific, the $NN \rightleftharpoons \Delta N$ t matrix calculated from Eq. (1) in the channel $^1D_2(NN) \rightleftharpoons {}^5S_2(\Delta N)$ is much stronger than those in other channels. This simply reflects the fact that NN scattering in $^1D_2$ has the largest inelasticity. In a previous paper[3] we have shown that the consistency of the $\pi NN \rightleftharpoons \Delta N \rightleftharpoons NN$ dynamics with the NN scattering is essential to derive microscopically the phenomenological spreading potential of the Δ-hole model for pion-nucleus scattering. In this Letter we will further show that the same dynamics affords the key to an understanding of the pion absorption on ^{3}He. By using the BL model Eq. (1), the pion absorption operator is cast in the form [Fig. 1(a)]

$$T_{NNN,\pi NNN}(E) = A_{NNN,\Delta NN}(E) \times G_{\Delta NN}(E)(V')_{\Delta NN,\pi NNN}. \tag{2}$$

The subscripts NNN, ΔNN, and πNNN denote projections onto the corresponding subspaces. $G(E)$ is the propagator for the NNN or ΔNN system in the form

$$G(E) = [E - H_0 - V_D(E)]^{-1}, \tag{3}$$

where the complex Δ self-energy $V_D(E)$ appears only in the ΔNN space.

The full calculation of the reaction with all complications of the four-body problem is clearly intractable. To proceed, we carry out the calculation in the space which contains no more than one pion or one Δ. We further neglect any two-baryon interactions in the four-body πNNN intermediate states. Then we can follow the Faddeev method to separate the operator $A(E) = \sum_{i\neq j} A_{ij}(E)$ into two parts,

$$A_{ij}(E) = \delta_{ij} t_i(E) + W_{ij}(E), \tag{4}$$

where $t_i(E)$ is the two-baryon t matrix calculated in the $NN \oplus N\Delta \oplus NN\pi$ subspace (the label i denotes a three-body channel with the ith nucleon being a spectator). The first term is the two-body mechanism as shown in Fig. 1(b). The three-body operator $W_{ij}(E)$ [Fig. 1(c)] satisfies

$$W_{ij}(E) = \bar{\delta}_{ij} t_i(E) G(E) t_j(E) + t_i(E) G(E) \sum_{k\neq i} W_{kj}(E) \tag{5}$$

with $\bar{\delta}_{ij} = 1 - \delta_{ij}$. The detailed derivations of the above equations will be given in a separate paper.

The most difficult part of our task is the calculation of Eq. (5) which involves intermediate states with NNN breakup cuts. We employed the subtraction method of Kloet and Tjon[4] in the calculation of driving them and achieved an accuracy of better than 5% by using a very large number of integration points. We further follow Ref. 4 to estimate the higher-order terms of Eq. (5) by using Padé approximation. Because the computation time increases drastically as the number of channels, increases, the three-body mechanism W_{ij} is calculated by using only the $^1D_2(NN)$

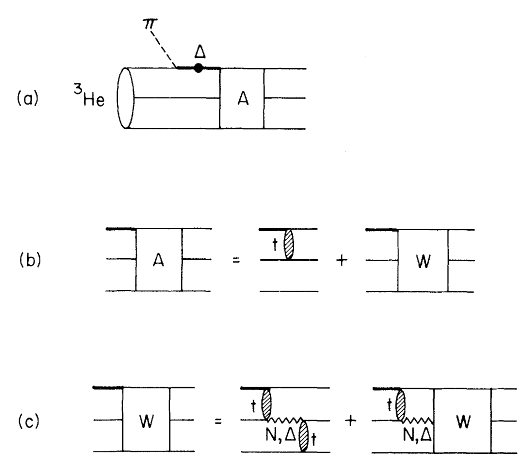

FIG. 1. (a) Schematic representation of the π absorption on ^{3}He in terms of the $\Delta NN \rightarrow NNN$ transition amplitude A. (b) The amplitude A is decomposed into two-body and three-body terms. (c) The latter is the solution of an integral equation in which the internal wavy line is either a nucleon or a dressed Δ.

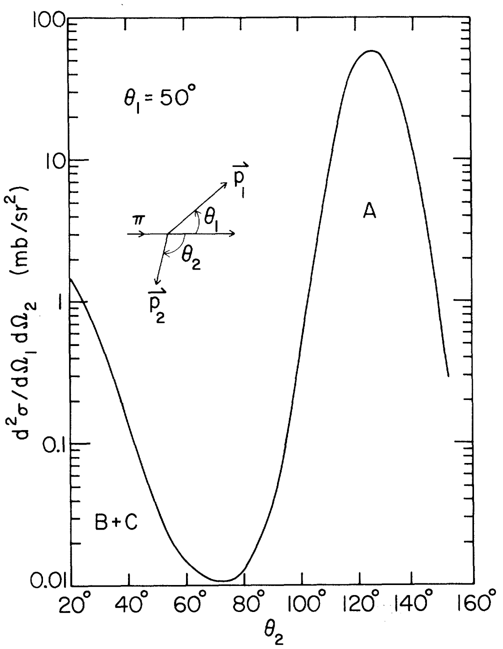

FIG. 2. Angular distribution of (π^+, pp). The processes (A), (B), and (C) are described in the text.

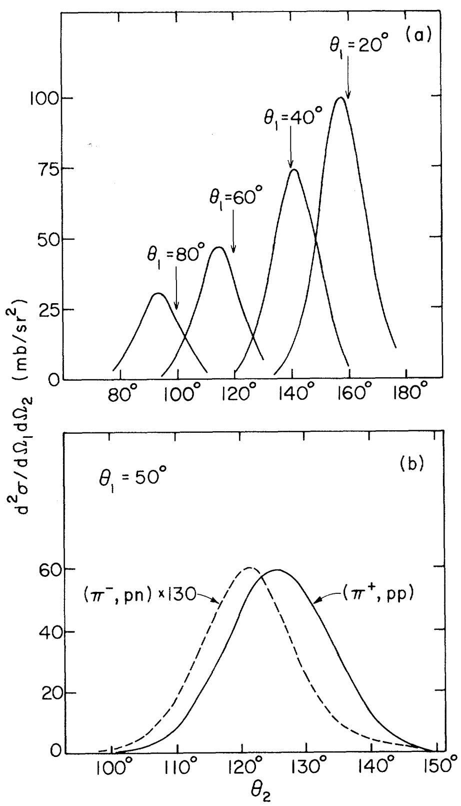

FIG. 3. (a) Angular distribution for (π^+, pp) with fixed θ_1. (b) Comparison of angular distribution for (π^+, pp) and (π^-, pn).

$\rightleftharpoons {}^5S_2(N\Delta)$ t matrix. However, all NN and $N\Delta$ partial waves with $l \leq 3$ are included in the calculation of two-body mechanisms.

We assume ^{3}He to have a simple Gaussian wave function in the s state, for simplicity. We carry out the integration of the absorption matrix elements of Eq. (2) over the ^{3}He wave function without any further approximations. Full details will be published elsewhere. But it must be emphasized, in particular, that an exact treatment of the nucleon Fermi motion in ^{3}He is essential to obtain the contribution from P-wave $N\Delta$ states for understanding the ratio $d\sigma(\pi^+, pp)/d\sigma(\pi^-, pn)$.

To understand our results, let us first consider kinematics of the (πNN) coincidence measurements. In the two-body process [Fig. 1(b)] with an antisymmetrized NNN state, the detected two-nucleon momenta $\vec{p}_1$ and $\vec{p}_2$ come from either (A) an interacting nucleon pair or from (B) one of an interacting pair and a spectator. $\vec{p}_1$ and $\vec{p}_2$ may also come from (C) the genuine three-body term W [Fig. 1(c)]. Our first task is to examine the relative importance between these three different mechanisms.

All calculations are performed for 165-MeV pions with the kinematics that the incident pion and $\vec{p}_1, \vec{p}_2$ are on the same plane. In Fig. 2 we show the results for (π^+, pp) at $\theta_1 = 50°$. A big bump around $\theta_2 = 125°$ is found to be dominated by the two-body process (A). The processes (B) and (C) become important only at $\theta_2 < 80°$ where the process (A) is completely suppressed. However, about 90% of the cross section in this region ($\theta_2 < 80°$) comes from the process (B) which is the tail of the two-body process. Consequently the *three-body term (C) can practically be neglected in any region.*

TABLE I. Contributions of the ΔN S and P waves to $d^3\sigma/d\Omega_1 d\Omega_2 dp_1$ (mb/sr^2 MeV) at $\theta_1 = 50°$, $\theta_2 = 120°$, and $p_1 = 565$ MeV/c. Important $NN \rightleftharpoons \Delta N$ partial waves are listed.

	$L_{\Delta N} = 0$	$L_{\Delta N} = 1$	Total
	NN ΔN	NN ΔN	
	$^1D_2$ $^5S_2$	$^3P_0$ $^3P_0$	
		$^3P_1$ $^3P_1 + {}^5P_1$	
		$^3P_2 + {}^3F_2$ $^3P_1 + {}^5P_2$	
(π^+, pp)	8.0×10^{-2}	1.4×10^{-3}	8.1×10^{-2}
(π^+, pn)	1.1×10^{-13}	9.7×10^{-4}	9.7×10^{-4}

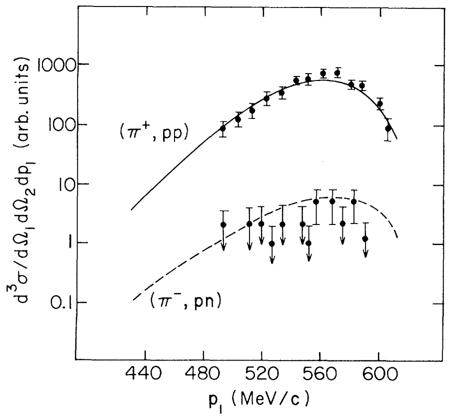

FIG. 4. Momentum spectra of (π^+, pp) and (π^-, pn) at $\theta_1 = 55°$ and $\theta_2 = 100°$. Experimental values are taken from Ashery *et al.* (Ref. 1). Units of the spectra are arbitrary but the correct relative normalization is used.

The dominance of the two-body process in absorption is more clearly seen in Fig. 3(a). For a given θ_1, there is a bump and its maximum is located at an angle very close to $\theta_2 \simeq 180° - \theta_1$. This is clearly the direct consequence of the two-body process. Hence the angular distribution of $\vec{p}_2$ with respect to $\vec{p}_1$ resembles very much that of $\pi^+ d \to pp$. The range of θ_2 in which the cross sections are significant reflects, of course, the momentum distribution of nucleons in ^{3}He.

We now turn to investigate the ratio $R = d\sigma(\pi^+, pp)/d\sigma(\pi^-, pn)$. The differential cross section for (π^-, pn) looks very similar to that of (π^+, pp) except that the maximum of the bump is shifted by about 5° and the magnitude is much smaller as illustrated in Fig. 3(b). As show in Table I, these differences are brought about by the fact that *the (π^+, pp) reaction is dominated by the S-wave ΔN state and the (π^-, pn) reaction by the P-wave ΔN state.* Clearly the ratio R is a function of angle and not an overall constant which one would have expected from isospin considerations alone.

Finally in Fig. 4 we compare our results for momentum spectra $d^3\sigma/d\Omega_1 d\Omega_2 dp_1$ with experimental values of Ashery *et al.* The ratio between (π^+, pp) and (π^-, pn) is very well reproduced. The shapes of the spectra are also in excellent agreement with experiment. The absolute values of the spectra are not reported by Ashery *et al.*, but we found that our predictions roughly agree with their preliminary data.

We conclude that the essential physics of the pion absorption by He can be successfully described by the two-body mechanism, provided that the essential $N\Delta \rightleftarrows NN$ dynamics in different partial waves are determined from NN scattering. The three-body absorption mechanism (mediated by two-body interaction) is found to be very small. From the present calculation and the study[3] of the spreading potential of the isobar-hole model, the two-body process $\pi NN \to \Delta N \to NN$ seems to be the essential absorption mechanism. It is desirable that this mechanism be further tested quantitatively in more coincidence measurements of absorption from He and heavier nuclei.

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