Angular distributions following three-nucleon pion absorption

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We present an analysis of the energy and angular distributions of nucleons following three-nucleon pion absorption. Three-nucleon absorption is treated as a one-step process whose transition matrix element is constant with respect to the energy of the final state nucleons. The inclusion of partial wave amplitudes for incident pions of angular momentum less than two shows good agreement with the experimental data in the delta-resonance region.

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Pion absorption on light nuclei is believed to proceed primarily through a mechanism in which a $T = 0$ nucleon pair is involved coherently, while the other nucleons behave as spectators. Although the quasideuteron absorption channel accounts for a large fraction of the total absorption cross section, it cannot explain all of the strength of absorption, particularly in heavy nuclei. The status of pion absorption studies can be found in recent review papers [1–3].

The next simplest absorption channel is one in which three nucleons participate in absorbing the momentum and energy of the pion. There are two useful limits one can consider in the description of these three-nucleon absorption events. The first limit is that absorption takes place as a two-step process. Two-step processes are those in which the pion is absorbed on a quasideuteron pair and an additional nucleon is involved either through a pion-nucleon interaction prior to absorption [initial state interaction (ISI)], or through a nucleon-nucleon interaction after pion absorption [final state interaction (FSI)]. Up to now there has been no clear quantitative evidence for the existence of such processes in pion absorption in light nuclei. Nevertheless, several calculations have in different ways modeled multinucleon absorption processes as a two-step process [4–10].

The second limit, which is the one which we consider here, is that all three nucleons participate coherently in the absorption. No characteristics of the individual nucleons in the three-nucleon system are important and the process is reduced to the interaction of a pion with the nucleus or the group of nucleons as a whole. In our previous papers, in this limit, we examined the effect of isospin on the ratios of observed three-nucleon absorption cross sections as well as the energy dependence of the cross sections [11,12]. In this paper, we calculate the expected angular distributions of final-state nucleons emitted after three-nucleon pion absorption, with the assumption that the matrix element is constant. This assumption is consistent with the observed phase space energy distributions found in three-nucleon pion absorption experiments on ^{3}He [2].

We will restrict ourselves to the results of experiments which measure pion absorption on three-nucleon targets. The most recent kinematically complete experimental results on three-nucleon absorption in ^{3}He [13–19] and ^{3}H [20] agree that the contribution of $3N$ absorption processes to the total absorption cross section is significant and on the order of 30% for energies in the Δ-resonance region.

Studying three-nucleon targets is advantageous because one eliminates the effects of interference from other possible multinucleon absorption channels. The restriction to a three-body system also simplifies matters by allowing one to analytically decompose the cross section into a kinematical factor which includes angular momentum, and a dynamical factor, the matrix element [21]. This is in general not possible for N-body systems with $N \geq 4$. In these cases, one must treat the angular momentum as part of the matrix element [22,23].

In our treatment we factor the angular momentum out of the transition matrix and include it with the phase space factor as a kinematical factor. Our kinematical factor consists of the product of the phase space factor and the angular momentum factor, and what remains in the transition matrix is the dynamic component of the cross section.

The differential cross section for the pion absorption reaction,

$$\pi + (3N) \rightarrow N_1 + N_2 + N_3, \tag{1}$$

is given in the helicity representation by the expression [24]

$$d\sigma_{3N} = \sum_{\lambda_1,\lambda_2,\lambda_3} \sum_{\lambda_\pi,\lambda_{3N}} \left(\frac{2\pi}{|\mathbf{p}_\pi|}\right)^2 \times |\langle p_1\lambda_1 p_2\lambda_2 p_3\lambda_3|S|p_\pi\lambda_\pi p_{3N}\lambda_{3N}\rangle|^2 d\rho_{3N}, \tag{2}$$

where the expression in brackets represents the S matrix corresponding to reactions starting with a pion and

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a three-nucleon system, and ending with three individual nucleons in a given final state, and $d\rho_{3N}$ is the invariant three-nucleon phase space volume. $p_1\lambda_1$, $p_2\lambda_2$, and $p_3\lambda_3$ are the four-momenta and helicities of the final three nucleons, $p_\pi\lambda_\pi$ and $p_{3N}\lambda_{3N}$ are the four-momenta and helicities of the initial pion and three-nucleon system, and $\mathbf{p}_\pi$ is the momentum of the incoming pion. Using momentum and energy conservation, the invariant three-nucleon phase space volume is a function of five independent variables and can be written as

$$d\rho_{3N} = dE_1 dE_2 d\phi_1 d\cos(\theta_1) d\phi_{1,2}, \qquad (3)$$

where θ_1 and ϕ_1 are the polar and azimuthal angles of $\mathbf{p}_1$, and $\phi_{1,2}$ is the azimuthal angle between $\mathbf{p}_1$ and $\mathbf{p}_2$.

In the case of an unpolarized beam and target, with no measurement of the final polarization, after averaging over initial and summing over final helicities and replacing λ_π by its value 0, the expression becomes [24–26]

$$d\sigma_{3N} = \frac{4\pi^2}{|\mathbf{p}_\pi|^2}(2s_{3N}+1)^{-1} \times \sum_{\lambda_1,\lambda_2,\lambda_3}\sum_{\lambda_{3N}} |\langle p_1\lambda_1 p_2\lambda_2 p_3\lambda_3|S(W)|\lambda_{3N}\rangle|^2 d\rho_{3N}, \qquad (4)$$

where s_{3N} is the spin of the three-nucleon system. In this expression we have required that the diagonal elements of the S matrix be relativistic invariants and have replaced the dependence on p_π and p_{3N} with the dependence on the pion–three-nucleon invariant mass W.

In order to correlate the angular distribution to the angular momentum of the system it is necessary to transform the angles ϕ_1, θ_1, and $\phi_{1,2}$ to the Euler angles α, β, and γ. We have chosen the z axis of our system to be the direction of the incident pion, and the Euler angles such that α and β correspond to the azimuthal and polar angles between the z axis and the direction of momentum of an arbitrarily chosen final-state particle (the z' axis). The angle γ represents an arbitrary rotation around the z' axis. The transformation between the Euler angle representation and the angular momentum of a system is given by the standard D matrix

$$\langle\alpha\beta\gamma|JKM\rangle = D^{J*}_{MK}(\alpha,\beta,\gamma) = e^{-iM\alpha} d^J_{MK}(\beta) e^{-iK\gamma}, \qquad (5)$$

where J is total angular momentum of the pion–three-nucleon system, $J = |\mathbf{J}_{(^3\mathrm{He},^3\mathrm{H})} + \mathbf{l}_\pi|$. In our model, the requirement of a one-step process means that the internal nucleon spin and angular momentum degrees of freedom are unimportant, and one considers the coupling of the angular momentum of the incident pion with the angular momentum of the ^{3}He nucleus. $\mathbf{J}_{(^3\mathrm{He},^3\mathrm{H})}$ is the total angular momentum of the ^{3}He or ^{3}H target, and $\mathbf{l}_\pi$ is the relative angular momentum between the pion and the three-nucleon system. M is the projection of the total angular momentum $\mathbf{J}$ on the z axis in the original coordinate system, in this case the pion beam line, and K is the projection on the z' axis in the rotated coordinate system, in this case the direction of a selected outgoing nucleon in the center of mass system. With our selection of the z axis, M corresponds to λ_{3N}. We can now expand S-matrix elements in the individual momentum basis using Eq. (5):

$$\langle p_1\lambda_1 p_2\lambda_2 p_3\lambda_3|S(W)|M\rangle = \frac{1}{(2\pi)^{3/2}}\sum_{J,K}\left(J+\frac{1}{2}\right) D^{J*}_{MK}(\alpha,\beta,\gamma)\langle KE_1E_2\lambda_1\lambda_2\lambda_3|S_J(W)|M\rangle. \qquad (6)$$

Inserting Eq. (6) into Eq. (4), using the relation

$$D^{J'}_{MK'}(\alpha,\beta,\gamma)D^{J*}_{MK}(\alpha,\beta,\gamma) = (-)^{(K-M)}\sum_{l=|J'-J|}^{J'+J}\langle J'MJ-M|l0\rangle\langle J'K'J-K|l(K'-K)\rangle D^l_{0(K'-K)}(\alpha,\beta,\gamma), \qquad (7)$$

and integrating over γ, the differential cross section can be written as

$$d\sigma_{3N} = \frac{1}{2\pi|\mathbf{p}_\pi|^2}(2s_{3N}+1)^{-1}\sum_{J,J'}\left(J+\frac{1}{2}\right)\left(J'+\frac{1}{2}\right)\sum_l d^l_{00}(\beta)\sum_{K,M}(-1)^{(K-M)}\langle J'MJ-M|l0\rangle\langle J'KJ-K|l0\rangle \times \sum_{\lambda_1,\lambda_2,\lambda_3}\langle KE_1E_2\lambda_1\lambda_2\lambda_3|S_J(W)|M\rangle\langle KE_1E_2\lambda_1\lambda_2\lambda_3|S_{J'}(W)|M\rangle^* dE_1dE_2d\alpha d\cos\beta. \qquad (8)$$

In our definition of quantization axis α and β correspond to ϕ and θ, and we get the final angular distribution:

$$\frac{d\sigma_{3N}}{d\phi d\cos\theta} = \sum_{J,J'}\sum_K\sum_l\left(J+\frac{1}{2}\right)\left(J'+\frac{1}{2}\right)\langle J'KJ-K|l0\rangle|A^{2J,2J'}_{2K}|^2 P_l(\cos\theta), \qquad (9)$$

where $|A^{2J,2J'}_{2K}|^2$ are the amplitudes defined by the expression

$$|A_{2K}^{2J,2J'}|^2 = \frac{1}{2\pi|\mathbf{p}_\pi|^2(2s_{3N}+1)} \sum_{\lambda_1,\lambda_2,\lambda_3} \sum_M (-1)^{(K-M)} \langle J' M J - M | l0 \rangle \times \int \langle K E_1 E_2 \lambda_1 \lambda_2 \lambda_3 | S_J(W) | M \rangle \langle K E_1 E_2 \lambda_1 \lambda_2 \lambda_3 | S_{J'}(W) | M \rangle^* dE_1 dE_2. \tag{10}$$

The cross section for pion absorption on three nucleons as defined in Eq. (4) is a fivefold differential quantity. It is common practice in kinematically complete experiments to reduce the number of differential quantities to two by integrating over the final reaction angles. In that case the cross section depends only on the energies of two of the final-state nucleons. This leads to the standard representation of the three-body reaction in the form of a Dalitz diagram. The characteristic feature of the two-dimensional Dalitz diagram (E_1, E_2) is that the event density over the area inside the kinematically allowed region is proportional to the square of the matrix element, while the kinematic contribution is uniformly distributed over the region. No significant deviation from a uniform density in the Dalitz diagram has been reported in the three-nucleon pion absorption experiments, indicating that the matrix element is roughly constant. In our case the condition

$$\frac{d\sigma_{3N}}{dE_1 dE_2} = \text{const} \tag{11}$$

is satisfied if

$$\langle K E_1 E_2 \lambda_1 \lambda_2 \lambda_3 | S_J(W) | M \rangle \langle K E_1 E_2 \lambda_1 \lambda_2 \lambda_3 | S_{J'}(W) | M \rangle^*$$

is not a function of E_1 and E_2. As a consequence, the final momentum distributions of the nucleons also show no deviations from the expected constant matrix element distribution. One must be aware, however, that the information from the Dalitz diagram, because of the integration over the final reaction angles, has no dependence on the angular momentum of the interacting pion–three-nucleon system.

We will now examine the angular distributions which one should observe in three-nucleon absorption on ^{3}He. As already mentioned, by assuming that three-nucleon pion absorption is a one-step process, we remove the dependence on the internal structure of the ^{3}He nucleus. The only quantities which enter the calculation are the total ^{3}He angular momentum $J_{^3\mathrm{He}} = \frac{1}{2}$ and the pion–three-nucleon system relative angular momentum $\mathbf{l}_\pi$. This means our final angular distribution becomes

$$\frac{d\sigma_{3N}}{d\phi\, d\cos\theta} = \sum_{J=|\mathbf{J}_{^3\mathrm{He}}-\mathbf{l}_\pi|}^{|\mathbf{J}_{^3\mathrm{He}}+\mathbf{l}_\pi|} \sum_{J'=|\mathbf{J}_{^3\mathrm{He}}-\mathbf{l}_\pi|}^{|\mathbf{J}_{^3\mathrm{He}}+\mathbf{l}_\pi|} \sum_K \sum_l \left(J+\frac{1}{2}\right)\left(J'+\frac{1}{2}\right) \langle J' K J - K | l0 \rangle |A_{2K}^{2J,2J'}|^2 P_l(\cos\theta). \tag{12}$$

From Eq. (10) the amplitudes must satisfy the symmetry relation $|A_{2K}^{2J,2J'}|^2 = -|A_{-2K}^{2J,2J'}|^2$. The results for the first few pion-^{3}He relative angular momenta are given below.

For $l_\pi = 0$,

$$\frac{d\sigma_{3N}}{d\phi\, d\cos\theta} = \sqrt{2}|A_1^{1,1}|^2. \tag{13}$$

For $l_\pi \le 1$,

$$\frac{d\sigma_{3N}}{d\phi\, d\cos\theta} = \sqrt{2}|A_1^{1,1}|^2 - 4(|A_1^{3,3}|^2 - |A_3^{3,3}|^2) + 4\sqrt{2}|A_1^{1,3}|^2 P_1(\cos\theta) + 4[|A_1^{3,3}|^2 + |A_3^{3,3}|^2] P_2(\cos\theta). \tag{14}$$

For $l_\pi \le 2$,

$$\begin{aligned}\frac{d\sigma_{3N}}{d\phi\, d\cos\theta} &= \sqrt{2}|A_1^{1,1}|^2 - 4(|A_1^{3,3}|^2 - |A_3^{3,3}|^2) + 3\sqrt{6}(|A_1^{5,5}|^2 - |A_3^{5,5}|^2 + |A_5^{5,5}|^2) \\ &+ \left[4\sqrt{2}|A_1^{1,3}|^2 - \frac{12}{\sqrt{5}}(\sqrt{6}|A_1^{3,5}|^2 + 2|A_3^{3,5}|^2)\right] P_1(\cos\theta) \\ &+ \left[6\sqrt{2}|A_1^{1,5}|^2 + 4(|A_1^{3,3}|^2 + |A_3^{3,3}|^2) - 3\sqrt{\frac{3}{7}}(4|A_1^{5,5}|^2 + |A_3^{5,5}|^2 + 5|A_5^{5,5}|^2)\right] P_2(\cos\theta) \\ &+ \frac{12}{\sqrt{5}}[2|A_1^{3,5}|^2 + \sqrt{6}|A_3^{3,5}|^2] P_3(\cos\theta) + \frac{9}{\sqrt{7}}[2|A_1^{5,5}|^2 + 3|A_3^{5,5}|^2 + |A_5^{5,5}|^2] P_4(\cos\theta).\end{aligned} \tag{15}$$

We can reduce the number of parameters required by the formalism if we consider another angular quantity of interest in the description of a three-nucleon absorption event, namely, the plane angle ξ. The plane angle is defined as the angle between the perpendicular to the plane of the three outgoing protons in the center-of-mass system and the beam axis (see Fig. 1). Measurement of the plane angle provides a simpler experimental test of the formalism, as it involves in the case of three identical particles, fewer free parameters than the final nucleon polar angle distribution.

One can apply the same formalism as described above, except that in this case the quantum number K is defined as the projection of the final-state angular momentum on the new z' axis, which we have taken to be the normal of the plane spanned by the final-state nucleons in their center-of-mass system. With this choice of quantization axis, the Euler angles α and β correspond to a set of angles η and ξ. While the form of Eq. (9) remains the same, the choice of a different quantization axis changes the meaning of the amplitudes. In the new case, symmetry requires that for three identical particles in the final state the amplitudes $|B_{2K}^{2J,2J'}|^2$ and $|B_{-2K}^{2J,2J'}|^2$ are equal. The resulting distributions for the plane angle for an incident pion of angular momentum up to $l \leq 2$ are given below.

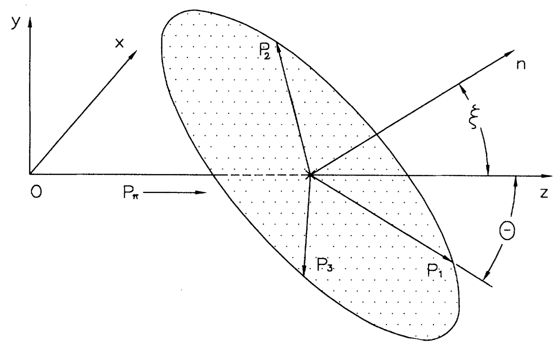

FIG. 1. A depiction of the final state following three-nucleon pion absorption in the center-of-mass system. θ is the angle of an outgoing proton, ξ is plane angle defined in the text. The shaded region depicts the plane formed by the three nucleons in the center-of-mass system.

For $l_\pi = 0$,

$$\frac{d\sigma_{3N}}{d\eta d\cos\xi} = \sqrt{2}|B_1^{1,1}|^2. \tag{16}$$

For $l_\pi \leq 1$,

$$\frac{d\sigma_{3N}}{d\eta d\cos\xi} = \sqrt{2}|B_1^{1,1}|^2 - 4(|B_1^{3,3}|^2 - |B_3^{3,3}|^2) + 4(\sqrt{2}|B_1^{1,3}|^2 + |B_1^{3,3}|^2 + |B_3^{3,3}|^2)P_2(\cos\xi). \tag{17}$$

For $l_\pi \leq 2$,

$$\begin{aligned}\frac{d\sigma_{3N}}{d\eta d\cos\xi} &= \sqrt{2}|B_1^{1,1}|^2 - 4(|B_1^{3,3}|^2 - |B_3^{3,3}|^2) + 3\sqrt{6}(|B_1^{5,5}|^2 - |B_3^{5,5}|^2 + |B_5^{5,5}|^2)\\ &+ \Bigg[2\sqrt{2}(2|B_1^{1,3}|^2 + 3|B_1^{1,5}|^2) + 4(|B_1^{3,3}|^2 + |B_3^{3,3}|^2)\\ &-3\sqrt{\frac{3}{7}}(|B_1^{3,5}|^2 - 8|B_3^{3,5}|^2 + 4|B_1^{5,5}|^2 - |B_3^{5,5}|^2 - 5|B_5^{5,5}|^2)\Bigg] P_2(\cos\xi)\\ &+3\sqrt{\frac{3}{7}}[8|B_1^{3,5}|^2 + |B_3^{3,5}|^2 + \sqrt{3}(2|B_1^{5,5}|^2 + 3|B_3^{5,5}|^2 + |B_5^{5,5}|^2)]P_4(\cos\xi).\end{aligned} \tag{18}$$

One can see that in the description of the plane angle distribution only Legendre polynomials of even order enter, and the distribution is symmetric around 90° and involves fewer parameters.

Up to this point we have developed a general formalism for the description of the reaction of pion absorption on three nucleons. Deviations from isotropic angular distributions of final-state nucleons in three-nucleon pion absorption have been observed in the Δ-resonance region [16,17,19]. These angular deviations can be explained in the framework of our formalism without affecting the observed uniform event density in the Dalitz plot.

We apply the formalism to the final nucleon angular distributions for pion absorption on ^{3}He measured by Smith *et al.* [17]. The differential cross section in the laboratory system shown in Fig. 2(a) exhibits the expected Legendre polynomial shape. Figure 2(b) shows the differential cross section in the π-^{3}He center-of-mass system. The transformation from the laboratory system to the center-of-mass system has been done assuming a constant matrix element. While in a two-body final state there is a one-to-one correspondence between the energy and angle

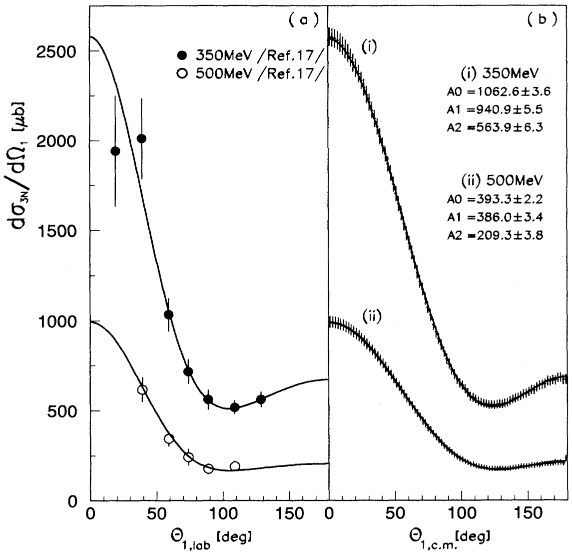

FIG. 2. Differential cross section for the reaction $\pi^+ + ^3$ He $\rightarrow ppp$ for pion energies of 350 and 500 MeV: (a) data and fit in the laboratory system from Smith *et al.* [17]; (b) distribution in center-of-mass system obtained by Monte Carlo calculation assuming constant matrix element. The error bars are the statistical errors of the Monte Carlo calculation. The coefficients are from the fit of the distribution using Eq. (19).

of an outgoing particle, in the case of a three-body final state such a correlation does not exist so a Monte Carlo technique must be used. In the Monte Carlo, we generated a three-body phase space distribution and weighted it by the experimentally measured lab angular distribution to determine the center-of-mass angular distribution. Following the expression for the differential distribution Eq. (9), we fit the differential cross section in the center-of-mass system by a sum of the Legendre polynomials:

$$\frac{d\sigma_{3N}}{d\phi d\cos\theta} = \sum_l A_l P_l(\cos\theta). \tag{19}$$

Extremely good agreement was shown using only Legendre polynomials of up to second order [the coefficients corresponding to the fit are shown in Fig. 2(b)]. From Eq. (9) this would correspond to pion angular momentum values of $l_\pi = 0$ and 1.

Because of the limited solid angle over which the experiment was performed one cannot exclude with certainty absorption of pions with $l_\pi > 1$. Nevertheless, our model gives a physical basis for using a Legendre polynomial fit in describing the measured angular distribution. A large solid angle measurement such as one which could be made with the large acceptance detector system (LADS) [18,28] would be able to determine conclusively the range of angular momentum brought in by the pion in the three-nucleon absorption mode.

To conclude, in this paper, we have examined for the first time the angular distributions one would expect by treating three-nucleon pion absorption as a coherent one-step process. Using our model, with the assumption of a flat phase space energy distribution [13,27], we are able to reproduce the angular distributions of an outgoing nucleon observed in absorption experiments at 350 MeV and 500 MeV [17] with pions of angular momentum $l_\pi = 0$ and 1. Furthermore, we have presented a calculation of the shape of the expected angular distribution of the plane angle following three-nucleon pion absorption. From the measurement of this angle one can completely determine the role of angular momentum in three-nucleon absorption.

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