# Evidence for Direct Triton Knockout in the $^4$He$(\pi,\pi' t)p$ Reaction

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Angular correlation functions for the $^4$He$(\pi^\pm,\pi^\pm{}' t)p$ reaction at the incident energy $T_\pi = 180$ MeV and at four pion scattering angles have been measured. The $^4$He$(\pi^\pm,\pi^\pm{}' t)p$ data complement previous $^4$He$(\pi^\pm,\pi^\pm{}' p)t$ results by greatly extending the available range of proton emission angles. We calculate angular correlation functions of the cross sections with three different quasifree knockout models, and we show that direct triton knockout is crucial to an understanding of the data.

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Knockout of $\alpha$ particles from nuclei by the $(p,p'\alpha)$ and $(\alpha,2\alpha)$ reactions have been studied for a wide range of targets and incident energies [1] and have provided information on the existence of $\alpha$ clusters in the nuclear surface. Much less is known about knockout of the three-nucleon clusters, $^3$He and $^3$H $(t)$. In this work, we investigate triton and proton knockout from $^4$He using $\pi^+$ and $\pi^-$ beams at incident energy $T_\pi = 180$ MeV, near the $P_{33}$ [$\Delta(1232)$] $\pi$-nucleon resonance. $^4$He is the best possible target for a study of triton and proton knockout because approximately 90% of the total proton momentum distribution in $^4$He can be attributed to the $p+t$ state (at small relative momentum) [2]. We show that the strong isospin dependence of the elementary $\pi$-nucleon force can be used to distinguish between direct proton knockout [3] and triton knockout, and we find that direct triton knockout is crucial to an understanding of the data.

If the $^4$He$(\pi,\pi' p)$ reaction were to proceed exclusively by quasielastic $\pi$-proton scattering, we would expect a cross-section ratio $\sigma(\pi^+,\pi^{+\prime} p)/\sigma(\pi^-,\pi^{-\prime} p)$ equal to 9 because the ratio of $\pi^+$-proton to $\pi^-$-proton elastic scattering amplitudes is 3 for the $P_{33}$ resonance. However, if the reaction were to proceed exclusively by quasielastic $\pi$-triton scattering, we would expect a cross-section ratio $\sigma(\pi^+,\pi^{+\prime} t)/\sigma(\pi^-,\pi^{-\prime} t)$ equal to 25/49 ($\approx 1/2$) because the $\pi^-$ interacts preferably with the two neutrons of the triton whereas the $\pi^+$ interacts preferably with the one proton. Early experiments [4] studying pion-induced knockout reactions on $^4$He at 110 and 160 MeV used cloud chambers, but the data were not sorted according to the angle of the knocked-out nucleon $N$. This fact limited the theoretical analysis to that of the $(\pi,\pi' N)$ cross sections integrated over the nucleon emission angle. Calculations by Mach *et al.* [5] indicated that a three-nucleon exchange (knockout) amplitude is important at large momentum transfer. However, the calculations failed to reproduce the ratio of total cross sections and this was interpreted as evidence for considerable initial- and/or final-state interaction effects. Tritons have been identified in the $^{12}$C$(\pi^\pm,\pi^\pm{}' t)^9$B [6] reaction but the statistics were insufficient to warrant a firm conclusion and no attempt was made to model the reaction.

The experiment [3] was performed using the energetic pion channel and spectrometer systems (EPICS) [7] at the Clinton P. Anderson Meson Physics Facility (LAMPF). EPICS was positioned at four angles $\theta_\pi^{\rm lab} = 30°$, 40°, 60°, and 80° on the left-hand side of the beam. In order to detect the particles emitted in coincidence with the pions, an array of plastic scintillators, each with a solid angle of 57 msr, was placed in the evacuated scattering chamber to the right-hand side of the beam at the angles $\theta^{\rm lab} = -30°$, $-45°$, $-60°$, $-75°$, and $-90°$. The experimental conditions and the analysis procedure were the same for incident $\pi^+$ and $\pi^-$. Angular correlation functions for the $\pi$-proton coincidence data from a recent $^4$He$(\pi^\pm,\pi^\pm{}' p)t$ experiment have been published by Jones *et al.* [3]. We have reanalyzed the raw data of that experiment and extracted $\pi$-triton coincidences.

The particle-dependent pulse height from the plastic scintillators and the particle's time of flight allowed identification and determination of the energy of the protons and tritons. In a plot of particle energy loss in the scintillators versus excitation energy $E_x(^4{\rm He})$, the $p+t$ final state (with a separate pulse-height and time-of-flight signature for protons and tritons) was cleanly separated from particles from other reaction branches. $\theta_p^{\rm c.m.}$ ($\theta_t^{\rm c.m.}$) is the proton (triton) ejectile angle in the c.m. of the recoiling mass-4 system. In the present work, the $(\pi,\pi' t)$ data are plotted together with the $(\pi,\pi' p)$ data as functions of $\theta_p^{\rm c.m.}$, since $\theta_p^{\rm c.m.} = \theta_t^{\rm c.m.} + 180°$. Some data had been obtained in Ref. [3] due to $\pi$-proton coincidences observed in detectors placed at angles larger than 90°. Those data have large error bars and correspond to lowenergy protons which were not well separated from the background. Data for the mirror reaction branch $n+{}^3\mathrm{He}$ have not been extracted from this experiment because these events fell below detector threshold. A more complete description of the experiment can be found in Ref. [3].

The incoming pion of total energy and momentum $(E_\pi, \mathbf{k}_\pi)$ scatters from $^4$He such that the pion's outgoing energy and momentum are $(E'_\pi, \mathbf{k}'_\pi)$. Energy $\Delta T_\pi$ and momentum $\mathbf{q}$ are transferred to the nucleus such that $\Delta T_\pi = E_\pi - E'_\pi$ and

$$\mathbf{q} = \mathbf{k}_\pi - \mathbf{k}'_\pi = \mathbf{k}_p + \mathbf{k}_t \,, \qquad (1)$$

where $\mathbf{k}_p$ and $\mathbf{k}_t$ are the momenta of the proton and triton in the final state. The excitation energy $E_x$ in $^4$He can be expressed in terms of $\Delta T_\pi$ and $q$ by

$$E_x({}^4\mathrm{He}) = [(\Delta T_\pi + m_a)^2 - q^2]^{1/2} - m_a \,, \qquad (2)$$

where $m_a$ is the mass of the $^4$He nucleus.

In order to obtain the double-differential cross sections (angular correlation functions) shown in Fig. 1, we have integrated the triple-differential cross sections $d^3\sigma/d\Omega_\pi \times d\Omega_p dE_x$ over the region of $E_x({}^4\mathrm{He})$ between 30 and 40 MeV. The condition that $E_x({}^4\mathrm{He})$ be greater than 30 MeV allowed us to identify recoiling tritons. At all pion angles, the $\pi^+$ angular correlation data (solid dots) peak near $\theta_p^{\mathrm{c.m.}} = 0°$ where proton knockout is expected to have its maximum. In sharp contrast, the $\pi^-$ angular correlation data (open dots) show a cross section near $\theta_p^{\mathrm{c.m.}} = 0°$ that is often much more than a factor of 9 smaller than for $\pi^+$. This observation is discussed extensively in Ref. [3]. However, the $\pi^-$ data do show maxima near $\theta_p^{\mathrm{c.m.}} = 180°$ because direct triton knockout is expected to generate a peak in the angular correlation. The $\pi^+$ data also display relative maxima near 180° but the cross sections for direct $\pi^-$-triton knockout are larger.

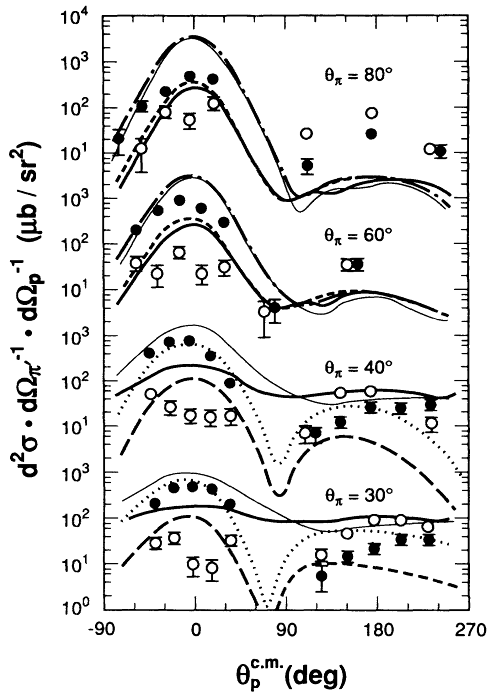


FIG. 1. Double-differential cross sections for the reactions $^4\mathrm{He}+\pi^+ \to p+t+\pi^+$ (solid dots) and $^4\mathrm{He}+\pi^- \to p+t+\pi^-$ (open dots) for $E_x$ integrated between 30 and 40 MeV. The solid curves represent our TAQ double-scattering calculations for $\pi^+$ (thin lines) and for $\pi^-$ (thick lines). At $\theta_\pi^{\mathrm{lab}} = 80°$ and 60° the dot-dashed ($\pi^+$) and dashed ($\pi^-$) curves show the TAQ single-scattering calculation. At $\theta_\pi^{\mathrm{lab}} = 40°$ and 30° the dotted ($\pi^+$) and long-dashed ($\pi^-$) curves represent the THREEDEE model calculation. Quasielastic proton scattering dominates at $\theta_p^{\mathrm{c.m.}} = 0°$ whereas quasielastic triton scattering dominates at $\theta_p^{\mathrm{c.m.}} = 180°$.

We have modeled the $^4\mathrm{He}(\pi,\pi' p)t$ reaction using the sum of the amplitudes for two processes: direct proton knockout and direct triton knockout. Angular correlation functions were calculated in this new two-amplitude quasifree (TAQ) model using the equation

$$\frac{d^3\sigma}{d\Omega_\pi d\Omega_p dk'_\pi} = |\phi(k_t) f_{\pi p}(\mathbf{k}_\pi, -\mathbf{k}_t, \mathbf{k}'_\pi, \mathbf{k}_p) + \phi(k_p) f_{\pi t}(\mathbf{k}_\pi, -\mathbf{k}_p, \mathbf{k}'_\pi, \mathbf{k}_t)|^2 k_p^2 \frac{dk_p}{dk'_\pi} \,. \qquad (3)$$

The function $\phi(k)$ is a momentum-space wave function of the $p+t$ system, and for the present calculations, we use a Gaussian wave function which reproduces the charge form factor of $^4$He. The momenta in Eq. (3) are not mutually independent as can be seen from Eq. (1). In $f_{\pi p}$, $-\mathbf{k}_t$ is the momentum of the proton before and $\mathbf{k}_p$ is the momentum of the proton after the collision. In $f_{\pi t}$, $-\mathbf{k}_p$ is the momentum of the triton before and $\mathbf{k}_t$ is the momentum of the triton after the collision. The $\pi$-proton amplitudes $f_{\pi p}$ were calculated from Ref. [8] and the $\pi$-triton amplitudes $f_{\pi t}$ were calculated according to Ref. [9]. This model gives peak values of the cross section when $k_t$ or $k_p$ are zero; i.e., the limiting cases of Eq. (3) are two independent quasifree scatterings. This model differs from other quasifree models by including the term with $f_{\pi t}$ in Eq. (3). All TAQ model calculations were done for $E_x = 35$ MeV.

The TAQ model calculations represented by the dot-dashed ($\pi^+$) and dashed ($\pi^-$) lines in Fig. 1 (only for the $\theta_\pi^{\mathrm{lab}} = 80°$ and 60° panels) assume a single-scattering approximation. This version of the TAQ model describes a two-body scattering problem which is being truncated, not the full scattering from four nucleons. In order to address the question of the degree of validity of the single-scattering approximation, which may not be accurate because the $\pi$-nucleon interaction is very strong, we have carried out a double-scattering TAQ calculation. The double-scattering calculations are shown as solid thin ($\pi^+$) and thick ($\pi^-$) lines in Fig. 1 (for all $\theta_\pi^{\mathrm{lab}}$) and approximately account for a "shadowing" effect due to scattering from the spectator particle. Our present TAQ calculations do not sufficiently describe the $\pi^-$-induced reaction. The inclusion of a shadowing effect does not sufficiently decrease the scattering probability to the level shown by the experiment, especially at $\theta_p^{\text{c.m.}}=0°$. At this point, our calculation with double scattering should be taken only as an indication of the size of the effect. For example, for $\pi^-$ scattering to $\theta_\pi^{\text{lab}}=80°$ and $\theta_p^{\text{c.m.}}=0°$, the effect is to decrease the cross section by roughly 20%.

Calculations from the one-nucleon knockout model THREEDEE [10] are represented by dotted ($\pi^+$) and long-dashed lines ($\pi^-$) in Fig. 1 (only for $\theta_\pi^{\text{lab}}=30°$ and 40°) and compared to the TAQ double-scattering predictions (solid lines). The THREEDEE calculations are made in the framework of the impulse approximation. They include (using a factorization approximation) the distortions of the incoming pion and target-nucleus system, the outgoing pion and residual-nucleus system, and the knocked-out proton and residual-nucleus system. The THREEDEE predictions for double-differential cross sections depend strongly on various distortions [3]. The back-angle rise in the THREEDEE predictions near $\theta_p^{\text{c.m.}}=180°$ is a consequence of distortions, not of triton knockout. These calculations do not include a $\pi$-triton amplitude $f_{\pi t}$ as in Eq. (3). The THREEDEE calculations at back angles are an order of magnitude smaller than the data for $\pi^-$.

One can estimate the effect of the momentum distribution on quasifree scattering cross sections by using the ansatz that the recoil momentum of the spectator particle ($k_{\text{spec}}$) is equal to its momentum before scattering. We calculated excitation energies where a $p+t$ momentum distribution has its maximum value ($k_{\text{spec}}=0$) and half-maximum value [2] ($k_{\text{spec}}=0.45\ \text{fm}^{-1}\approx 90$ MeV/$c$). The values of $E_x$ for $k_{\text{spec}}=0$ are listed in Table I in the columns denoted by $E_x^{\text{q.f.}}$. Deviations from $E_x^{\text{q.f.}}$ for $E_x$ such that $k_{\text{spec}}=90$ MeV/$c$ are indicated by the superscripts and subscripts in Table I. For example, at $\theta_\pi^{\text{lab}}=40°$, quasifree proton knockout occurs with maximal probability when $E_x=34$ MeV. With $E_x=33$ MeV, direct triton knockout occurs with roughly one-half of the maximal probability because the (spectator) proton is emitted with $\approx 90$ MeV/$c$. Also given in the table is the momentum transfer $q$ for each of the pion scattering angles with $E_x=35$ MeV.

TABLE I. The predicted centroids of quasifree peaks in the excitation energy spectra are given for all pion scattering angles in columns labeled $E_x^{\text{q.f.}}(\pi,\pi'p)$ and $E_x^{\text{q.f.}}(\pi,\pi't)$. For these values, the spectator particle is emitted with zero momentum ($k_{\text{spec}}=0$). The superscripts and subscripts give, if added to $E_x^{\text{q.f.}}$, the excitation energies corresponding to $k_{\text{spec}}\approx 90$ MeV/$c$, as discussed in the text. Subscripts are omitted when breakup is energetically forbidden. The momentum transfers $q$ are given for $E_x=35$ MeV.

| $\theta_\pi^{\text{lab}}$ (deg) | $q$ ($\text{fm}^{-1}$) | $E_x^{\text{q.f.}}(\pi,\pi'p)$ (MeV) | $E_x^{\text{q.f.}}(\pi,\pi't)$ (MeV) |
|---|---|---|---|
| 30 | 0.73 | $28^{+18}$ | $22^{+9}$ |
| 40 | 0.94 | $34^{+18}_{-12}$ | $22^{+11}$ |
| 60 | 1.35 | $47^{+22}_{-18}$ | $23^{+11}$ |
| 80 | 1.70 | $60^{+25}_{-22}$ | $26^{+12}$ |

We define an isospin ($T$) asymmetry $A_T(\theta_p^{\text{c.m.}})$, in analogy with the spin observable $A_y$, with the equation

$$A_T(\theta_p^{\text{c.m.}})=\frac{\sigma(\pi^+,\pi^{+\prime}X)-\sigma(\pi^-,\pi^{-\prime}X)}{\sigma(\pi^+,\pi^{+\prime}X)+\sigma(\pi^-,\pi^{-\prime}X)}, \quad (4)$$

where $X=p$ or $t$. In the plane-wave impulse approximation (PWIA) and for $P_{33}$ resonance dominance, the observable $A_T(\theta_p^{\text{c.m.}})$ is isotropic and equal to $+0.8$ for pure quasielastic proton knockout. For pure quasielastic triton knockout, we expect $A_T(\theta_p^{\text{c.m.}})$ to be isotropic and equal to $\approx -0.3$. These results are *independent* of the scattering angle of the pion and proton. Moreover, if the pion scattering excites $^4$He to a resonance state with pure isospin, its decay is governed exclusively by the properties of that state, and we expect $A_T=0$. Thus, exclusive, kinematically complete $\pi^+$ and $\pi^-$ scattering should easily distinguish between proton knockout, triton knockout, or resonance formation and decay for these reasons: the prediction of isotropy in $A_T(\theta_p^{\text{c.m.}})$ in the

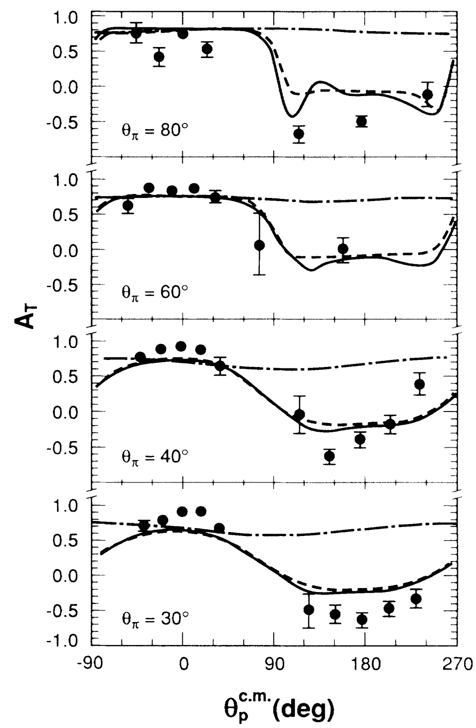


FIG. 2. Isospin asymmetry $A_T(\theta_p^{\text{c.m.}})$ [Eq. (4)] for the reactions $^4\text{He}+\pi^\pm\rightarrow p+t+\pi^\pm$, for $E_x$ integrated between 30 and 40 MeV. The data show large isospin asymmetries, changing from $+1.0$ near $\theta_p^{\text{c.m.}}=0°$ to $-0.6$ near $\theta_p^{\text{c.m.}}=180°$. The solid and dashed lines of the TAQ model qualitatively describe the data with and without double scattering and show the importance of direct triton knockout near $\theta_p^{\text{c.m.}}=180°$. The dot-dashed lines represent proton knockout calculations (with distortions) using THREEDEE [10]. These asymmetries are essentially isotropic, because that model does not include a $\pi$-triton amplitude such as $f_{\pi t}$ in Eq. (3).

case that a single amplitude is involved in the scattering, and the large values and different signs of asymmetry for quasifree proton and triton scattering.

The data for $A_T(\theta_p^{\rm c.m.})$ in Fig. 2 vary strongly with $\theta_p^{\rm c.m.}$ from near +1.0 in the kinematic region of quasifree proton knockout ($\theta_p^{\rm c.m.}=0°$), to about −0.6 in the kinematic region of quasifree triton knockout ($\theta_p^{\rm c.m.}=180°$). This result requires that at least two amplitudes contribute to the reaction. The TAQ model with the $\pi$-triton scattering amplitude successfully describes the sign reversal of $A_T(\theta_p^{\rm c.m.})$ with (solid lines) or without the shadowing effect (dashed lines). The prediction using THREEDEE (dash-dotted lines) with only a $\pi$-proton interaction is essentially isotropic (near the PWIA prediction of $A_T=+0.8$). This is our strongest evidence for direct triton knockout.

Use of different pion-nucleus optical potentials and proton-triton optical potentials in THREEDEE can affect the calculations of cross sections [3] by factors of 2 to 3; however, these changes yield values of $A_T(\theta_p^{\rm c.m.})$ which differ by less than 2%. The THREEDEE model calculations deviate slightly from $A_T(\theta_p^{\rm c.m.})=+0.8$ because of distortions and/or contributions from the $s$-wave $\pi$-nucleon interaction. The dependence of $A_T(\theta_p^{\rm c.m.})$ on variations of the TAQ model is also small, because shadowing effects in the TAQ model are similar for $\pi^-$- and $\pi^+$-induced reactions.

While there is ample evidence from $A_T(\theta_p^{\rm c.m.})$ that triton knockout is present, the TAQ model underestimates the magnitude of $A_T$ near $\theta_p^{\rm c.m.}=0°$ and 180° (Fig. 2). The TAQ description of the $\pi^-$-proton data near the quasifree proton angle is poor and the TAQ calculation of the $\pi^+$-proton cross section (Fig. 1) varies with proton angle more slowly than the data. The TAQ model may be improved by use of $^4$He wave functions such as in Ref. [2]. The largest variation between the model calculations is near $\theta_p^{\rm c.m.}=90°$ and −90°, where interference effects in the TAQ model are maximized, but where there are currently no data.

Clearly, additional physics issues need to be considered. Of these, nuclear resonance states may be important, but based on a recent compilation and study [11], we expect that we avoid much of the complicated nuclear structure of $^4$He below $E_x \approx 30$ MeV. Another possibility is a charge-exchange $(n,p)$ process which is expected to be particularly strong near $\theta_p^{\rm c.m.}=0°$ for $\pi^-$. The two-step charge-exchange reaction mechanism $(e,e'n)$ followed by $(n,p)$ was studied in a model of the exclusive reaction [12] $^4$He$(e,e'p)$. Calculations that combined the effects of $(n,p)$ charge exchange, meson exchange, and proton rescattering showed that an $(n,p)$ charge-exchange process increases the $^4$He$(e,e'p)$ cross section by about 10% [12]. Direct triton knockout was not included in that calculation.

Kyle *et al.* [13] have modeled the $^{16}$O$(\pi^\pm,\pi^{\pm\prime}p)$ reaction by including a $\Delta$-$N$ interaction. In that model a $\Delta$-induced proton knockout amplitude interferes with the quasifree proton knockout process. Understanding of the present data for $^4$He may improve with the application of such a model, but that model has not been extended yet to include a $\pi$-triton interaction.

We conclude that the isospin dependence of the $\pi$-triton interaction in the region of the $P_{3,3}$ resonance can be used to identify direct triton knockout from the nucleus. Experiments with $\pi^+$ and $\pi^-$ on other nuclei in which tritons (and possible $^3$He) are detected could provide evidence for the occurrence of preexisting clusters of mass 3. Exclusive scattering experiments with $\pi^+$ and $\pi^-$ on light nuclei should allow us to refine reaction models and nuclear wave functions. For the $^4$He$(\pi^\pm,\pi^{\pm\prime}t)p$ reaction, the direct $\pi$-triton scattering amplitude appears to be an essential component of the reaction mechanism.

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