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Pion absorption in ^{4}He above the delta resonance

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The reaction $^4\mathrm{He}(\pi^+,pp)pn$ was measured at T_π=500 MeV. The angular distribution of quasifree two-body absorption which was obtained agrees in detail with the free $\pi d \to pp$ reaction and scales according to the number of $T = 0$ pn pairs in ^{4}He. Possible evidence for pd final-state interactions is discussed. The extrapolated total cross section for four-body absorption is 2.5±0.6 mb, which is substantially less than predicted from a model based on $\Delta\Delta$ excitation.

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In this Rapid Communication we report results from a measurement of the $^4\mathrm{He}(\pi^+,pp)pn$ reaction at $T_\pi = 500$ MeV. Previous experiments that measured the energy dependence of pion absorption in ^{3}He [1–3] found larger two-body yields above the peak of the $\Delta(1232)$ resonance than expected from simple scaling arguments based on the quasideuteron absorption (QDA) model. The present measurement was intended to explore further the density dependence and validity of the QDA model at high energies.

Most studies of QDA have focused on energies near the Δ resonance, where the elementary $\pi d \to pp$ reaction mechanism is fairly well understood. In this region, the large momentum transfer required is accomplished through formation of an intermediate ΔN state with zero relative angular momentum. Selection rules then automatically lead to the dominance of absorption by p-wave pions on $^3S_1$ isoscalar pn pairs in all nuclei, in agreement with experiments [4].

An unresolved question concerns the absolute strength of the quasideuteron component of pion absorption. Calculations which incorporate the dynamics of the ΔN interaction within the nucleus predict a substantial density dependence for the QDA mechanism, resulting from a sensitivity to the "size" of the absorbing pair [5,6]. Experimental attempts to verify this density dependence have focused on the helium isotopes [7], where kinematically complete experiments are possible and distortions are minimized. In these studies, angular distributions of quasifree two-body absorption are compared directly to those for the free $\pi^+ d \to pp$ reaction, using the relative normalization to count the effective number of deuterons N_d. Enhancement or distortion of QDA is indicated by a departure of N_d from the known number of isoscalar pn pairs, which is 1.5 in ^{3}He and 3.0 in ^{4}He.

Quasifree angular distributions obtained from experiments so far appear identical in shape to those for the corresponding $\pi d \to pp$ reaction. For energies at and below the Δ, all measurements on ^{3}He [1,2,8] and ^{3}H [9] are consistent with $N_d = 1.5$. Above the Δ resonance a systematic increase of 15–30 % in the value of N_d is seen in ^{3}He [1,3]. For ^{4}He, Steinacher *et al.* [10] find $N_d = 3.0$ at 120 MeV, although their systematic error is 25%. Adimi *et al.* [11] measure a 30–40 % suppression of N_d at 114 and 162 MeV, which they attribute to pd final state interactions (FSI).

The apparent absence of any enhancement of QDA in ^{4}He is puzzling, since the average pn pair separation in this nucleus is half that of the deuteron. One possible explanation is that three- and four-body absorption, recently identified in ^{4}He, may interfere with the two-body channel. Another possibility is that pion distortions could lead to shadowing effects. At present, the dynamical origin and especially the relationship of these mechanisms to QDA is still unknown. Ohta *et al.* [5] used the Δ-hole model to estimate the magnitude of pion initial state interactions (ISI) in ^{4}He, and found they are sufficiently strong near the Δ to roughly cancel the 2–3-fold QDA enhancement expected from absorption on a smaller deuteron. However, no direct experimental evidence of such substantial ISI has been reported. At higher energies, shadowing effects due to ISI may diminish as the nucleus becomes more transparent to the pion. This might explain the $N_d > 1.5$ trend seen in ^{3}He, although other mechanisms may also be responsible, such as a binding correction to the pion energy, or absorption on $^1S_0$ isovector pn pairs. At the same time, the relative contribution of multinucleon absorption is expected to increase above the Δ. This expectation is based on models which generalize the two-body mechanism to include the excitation of multiple Δ's [12,13]. Substantial contributions to the total absorption cross section are predicted in ^{4}He above 300 MeV, where the creation of multiple Δ's becomes energetically favorable. Clearly, measurements on ^{4}He above the Δ are crucial to making further progress on understanding pion absorption.

The experiment was performed at the Los Alamos Meson Physics Facility using apparatus similar to that described in [3]. A positive 500 MeV pion beam with a momentum spread of 1.5% and a divergence of $\pm 2°$ was incident on a cylindrical 10 cm diameter liquid ^{4}He target at 4.1 K with 0.0127 cm Ni walls. An identical empty target cell was used for background subtraction. Reaction protons were detected at laboratory angles θ_1 ranging from 14° to 94° using a 1 GeV/c magnetic spectrometer with a 1.8% FWHM momentum resolution. The useable acceptance covered $\Delta p/p$ from -25% to $+50\%$ with an average solid angle of 1.82 msr. Scintillators provided a fast trigger and measured time of flight for mass identification.

Charged and neutral particles were detected in coincidence with protons in the spectrometer by a movable wall of 16 scintillator bars arranged in two layers. Each bar was 10 cm wide, 10 cm thick, and 1.6 m tall, centered vertically on the scattering plane. Each end of a bar was viewed by a 5 cm photomultiplier tube (PMT). The array was 2.8 m from the target and subtended a solid angle of 0.32 sr, providing a horizontal and vertical angular coverage of $\pm 16°$. Timing information from each PMT pair determined time of flight (TOF) and vertical position with resolutions of 0.6 ns and 6.0 cm (FWHM), respectively. Horizontal resolution was 10 cm. The energy threshold for protons was 40 MeV inside the target. Sixteen overlapping 0.16 cm thick scintillator paddles in front of the array discriminated between charged and neutral particles and provided E-ΔE information for particle identification. The TOF arm was nominally set to the angle θ_2 conjugate to θ_1 according to $\pi d \to pp$ kinematics.

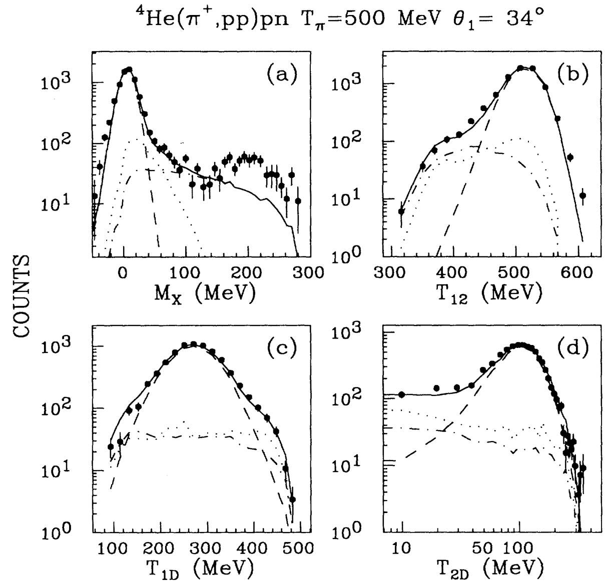

FIG. 1. (a) Missing mass spectrum for the ^{4}He(π^+,pp)X reaction at laboratory angle $\theta_1 = 34°$. Other plots show invariant energy distributions (see text) of pion absorption events cut on $M_X < 140$ MeV. Data are not corrected for TOF arm acceptance. Curves show fitted calculations—dashed line: $2N$ PWIA; dotted line: $3N$ PWIA; dot-dashed: $4N$ phase space; solid: sum of all three.

An ionization chamber upstream of the target continuously monitored beam current. Periodically, the pion flux was determined absolutely to an accuracy of about 5% using ^{11}C activation and a sampling scintillator to measure beam composition. This flux was checked with $\pi p \to \pi p$ and $\pi d \to pp$ measurements made independently using solid targets. The overall agreement with the known cross sections [14] was 3–5 %. The latter reactions were also used to perform energy and position calibration in the detectors. A fixed angle telescope for detecting backward scattered pions monitored the helium target thickness, which varied by less than 2%. The overall normalization error was 6%.

Reaction identification was carried out using cuts on the missing mass M_X of the ^{4}He(π^+,pp)X reaction, shown in Fig. 1(a) for a typical case at $\theta_1 = 34°$. We define $M_X = (E_m^2 - P_m^2)^{1/2} - M_d$, where M_d is the deuteron mass and E_m and P_m are the missing energy and missing momentum derived from the measured four-momenta $(E_1, \mathbf{P}_1)$ and $(E_2, \mathbf{P}_2)$ of the protons detected in the spectrometer and TOF arm, respectively. Missing mass resolution was around 20 MeV (FWHM) for most settings. Below the pion threshold ($M_X < 140$ MeV), the spectrum represents the excitation energy of the final state deuteron. The sharp increase in the reaction yield above the pion threshold is most likely due to breakup channels in which the pion was not absorbed. This unwanted contribution was eliminated from all other kinematic distributions by excluding events with $M_X > m_\pi$. The prominent peak around $M_X = 0$ is due largely to QDA, which leaves the spectator deuteron in its ground state. Other data shown in Fig. 1 are the invariant energy distributions $T_{12} = [(E_1+E_2)^2 - (\mathbf{P}_1+\mathbf{P}_2)^2]^{1/2} - M_1 - M_2$ and $T_{iD} = [(E_i+E_m)^2 - (\mathbf{P}_i+\mathbf{P}_m)^2]^{1/2} - M_i - M_X$, where i = 1,2. These variables are used in our fitting procedure described below.

The curves represent calculations which have been folded into a Monte Carlo program that incorporates the experimental acceptance, instrumental resolution, and kinematics cuts. These calculations are used to parametrize the data and extract strength estimates for two-, three-, and four-body absorption channels. A plane wave impulse approximation (PWIA) model of QDA similar to that described in [3] is used to simulate the two-body channel. This requires folding the free $\pi d \to pp$ cross section into a ^{4}He$\to d+d$ momentum distribution weighted with *ppd* three-body phase space. For simplicity, excitation of the spectator deuteron is neglected. Three-body absorption in ^{4}He is assumed to proceed through quasifree absorption on ^{3}He and ^{3}H clusters, evidence for which has been given by Steinacher [10] and Weber [15]. To simulate this, a ^{4}He$\to t+p$ momentum distribution is weighted with *pppn* four-body phase space. The $d+d$ momentum distribution of Morita *et al.* [16] was used, while the $t+p$ momentum distribution was taken from Schiavilla *et al.* [17]. Finally, four-body absorption is assumed to follow phase space. Details will be given in a forthcoming paper.

The sum of these calculations is simultaneously fitted to distributions of M_X, T_{12}, T_{1D}, and T_{2D} using a least-squares procedure which adjusts the individual normalization of each absorption channel. This global fitting procedure greatly improves the uniqueness of the fit and minimizes systematic bias arising from the instrumental resolution of any one variable. A typical fit is shown in Fig. 1. The fitted normalization constants obtained at each angle θ_1 are used by the Monte Carlo program to estimate the yield missed by the finite acceptance of the detectors and to extract cross sections for each of the absorption channels. This introduces some model dependence discussed shortly.

The angular distribution of the acceptance-corrected two-body differential cross section is shown in Fig. 2(a). The solid curve was obtained from fitting $\pi d \to pp$ reaction data at 500 MeV, measured in this experiment with the same detector configuration used to obtain the ^{4}He data. This curve has been scaled up to fit the data, giving $N_d = 2.96 \pm .03$. The excellent agreement between the shapes of the two distributions is strong evidence for the continued validity of the QDA model at this energy. Evidently, the increased nuclear density has little effect on the partial wave composition of the $\pi d \to pp$ reaction.

The model dependence of this result was estimated by repeating the global fit using the $d+d$ momentum distribution of Schiavilla *et al.* [16]. This gave $N_d = 3.34 \pm 0.04$, with a marginal decrease in the global fit χ^2. For each momentum distribution we also tried various kinematic prescriptions for evaluating the QDA PWIA matrix element. The final state prescription (FSP), which uses the invariant energy T_{12} [see Fig. 1(b)] of the detected protons, gave the lowest overall global χ^2, and the largest value for N_d. Other prescriptions produced a significant increase in the global χ^2, and a 10% decrease in N_d, similar to the uncertainty introduced by the choice of momentum distribution. For all cases no significant change in the shape of any of the extracted angular distributions occurred. A conservative estimate of N_d obtained by averaging all cases is $N_d = 3.0 \pm 0.3$, or $\sigma_{2N} = 1.14 \pm 0.11$ mb.

Although the value of N_d determined in this experiment appears "correct," the choice of PWIA prescriptions has an important bearing on the interpretation of this result. To see this we compare the data in Fig. 2(a) to the PWIA-predicted QDA angular distributions obtained by fixing the $d+d$ momentum distribution normalization

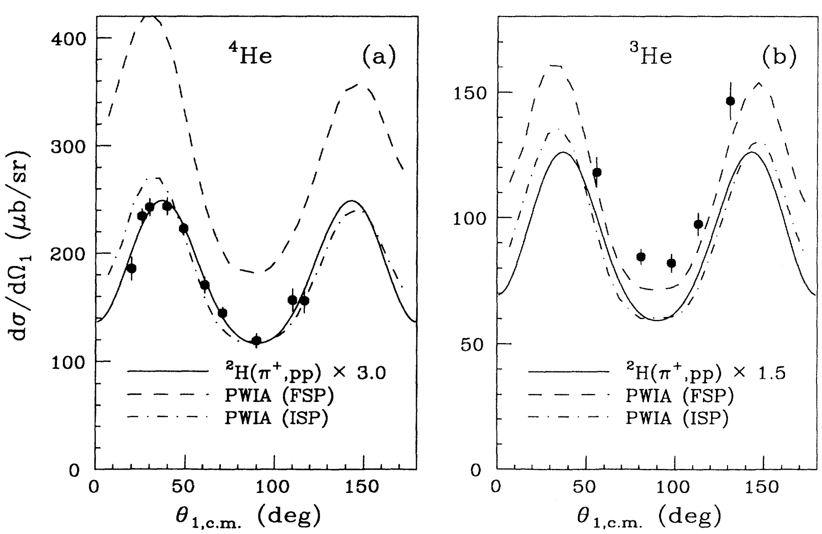

FIG. 2. Distributions in $\pi d \to pp$ center-of-mass system of quasifree two-body absorption in (a) ^{4}He (present measurement) and (b) ^{3}He [3] at T_π=500 MeV. PWIA calculations show the result of using final state prescription (FSP) and initial state prescription (ISP). Data were extracted from the fitting procedure described in text, using FSP and the ^{4}He$\to d+d$ momentum distribution of Morita. Only statistical errors are shown.

at 3.0 deuterons. In the case of the FSP, the resulting curve is much higher than the data, suggesting the expected deuteron number N_d is actually much larger than 3.0. This effect is expected in the FSP because the Q value of the reaction lowers the effective $(\pi d)_{\rm c.m.}$ energy where, in this case, the $\pi d \to pp$ cross section is larger. On the other hand, the initial state prescription (ISP), which ignores the binding of the quasideuteron, produces an angular distribution consistent with $N_d = 3.0$. Therefore, depending on the prescription used, the ^{4}He data is seen to be either substantially *suppressed* relative to PWIA or in agreement with PWIA.

A possible clue as to which prescription is more appropriate may be found in an earlier experiment on ^{3}He at 500 MeV. We show in Fig. 2(b) similar PWIA calculations compared to ^{3}He data previously published [3]. In this case a 30% *enhancement* in N_d was found, which is largely accounted for by the FSP calculation. On the other hand, if the ISP is assumed, some other process must account for the ^{3}He enhancement, such as a genuine density effect or possibly absorption on isovector pn pairs. However, those mechanisms should also enhance N_d in ^{4}He by at least as much, so that in either case a substantial suppression of cross section is indicated in ^{4}He.

At much lower energies, a similar suppression seen by Adimi *et al.* [11] was attributed to FSI between the recoiling spectator deuteron and one of the detected protons. A distorted wave calculation indicated that up to 30% of the QDA events in ^{4}He may be lost this way. As noted by those authors, these lost events may show up as enhancements in other parts of phase space normally associated with non-QDA processes. In our experiment, it appears that at least some of the missing QDA strength is picked up by the three-body quasifree absorption ($3N$ QFA) parametrization. The angular dependence of the fitted normalization constants [Fig. 3(a)] departs substantially from phase space at forward angles, and more closely resembles the laboratory frame angular dependence of QDA. From Fig. 1(a), the $3N$ QFA fit is seen to be most strongly constrained by the region of deuteron excitation $M_X = 40-60$ MeV. Although this is too large an excitation to be due purely to QDA, it is plausible that QDA + pd FSI may lead to excitations of this magnitude. In particular, nearly all of the excess counts (with respect to QDA) occur at small relative energies T_{2D} between p_2 and the unobserved deuteron [Fig. 1(d)], where FSI are potentially strongest. More analysis is planned to estimate the strength of these distortions and their relationship to the two-body channel. However, it seems likely that our value for N_d is a lower limit.

Finally, it is seen that the θ_1 dependence of the fitted $4N$ cross sections does not depart significantly from phase space [Fig. 3(b)], making plausible an extrapolation into unmeasured portions of phase space to obtain the total four-body cross section. This quantity has long been of interest since Brown *et al.* [18] proposed the double-Δ mechanism for four-body absorption. Using an SU(4) quark model derivation of the $\pi\Delta\Delta$ coupling constant, Schwesinger *et al.* [12] predicted $\sigma_{4N} = 12-30$ mb at the energy of this experiment. Our result is $\sigma_{4N} = 2.5 \pm 0.6$ mb, where the large error is dominated by statistics. This result can be considered an upper limit, since Fig. 1(a) shows that the maximum normalization of four-body phase space is strongly constrained by the region of excitation energy $E_X = 100-140$ MeV, where two- and three-body phase space is negligible. Since the extrapolation factor is large (≈ 10), any departure from phase space outside of our kinematic cuts could produce a significantly different result. For example, if we follow the procedure of Steinacher *et al.* [10] to estimate the pn soft-FSI contribution to σ_{4N} using the Watson-Migdal enhancement factor described in [7], we find $4N/(4N + \text{FSI}) \approx 0.5$. This reduces our estimate of σ_{4N} to an order-of-magnitude less than expected from the $\Delta\Delta$ model, and roughly in agreement with values obtained at much lower energies [10,15]. Clearly, in light of this result, more exclusive measurements are called for in addition to more detailed calculations which predict specific kinematic signatures.

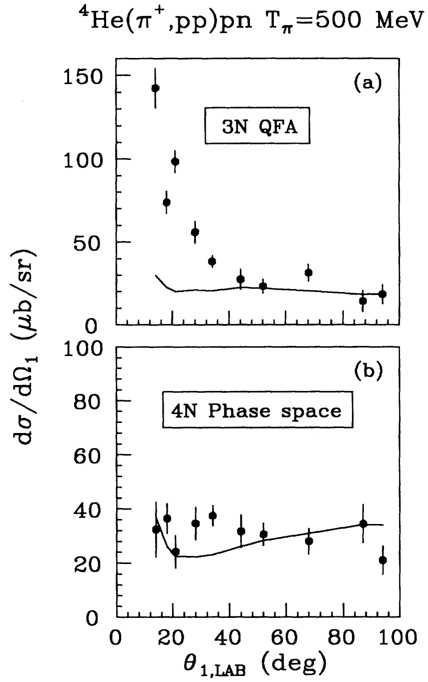

FIG. 3. Distributions in laboratory angle θ_1 of three-body quasifree absorption ($3N$ QFA) and four-body phase space obtained from fits to energy distributions similar to those shown in Fig. 1. Solid curves are unfitted calculations arbitrarily normalized to data. Data not corrected for TOF arm acceptance.

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