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^{4}He$(\pi,\pi'p)^{3}$H reaction: Quasifree and resonance scattering

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Exclusive ^{4}He$(\pi^{\pm},\pi^{\pm\prime}p)^{3}$H spectra in the excitation energy range between 21.5 and 44 MeV in ^{4}He were measured at $T_{\pi}=180$ MeV at several pion and proton angles. The cross section ratio $R_{\pi p}=\sigma(\pi^{+},\pi^{+\prime}p)/\sigma(\pi^{-},\pi^{-\prime}p)$ was found to be between 1 and 2 near 22 MeV which is in the region of the $J^{\pi}=2^{-}$, $T=0$ state. Between 25 and 40 MeV in the continuum, which comprises the giant dipole resonance and broad 2^{-} and 2^{+} states, $R_{\pi p}$ ranges from 0.22 to 45 in sharp contrast to the predicted values of ≈ 1 from a model assuming the entire yield is due to the sequential decay of a state of good isospin, and 6 to 9 from a distorted-wave impulse approximation calculation assuming quasifree proton knockout.

At incident pion energies near the $\Delta_{3/2,3/2}$ pion-nucleon resonance, pion inelastic scattering provides a probe of the isospin characteristics of nuclei due to the selectivity[1] of $\pi^{+}(\pi^{-})$ for exciting proton-proton-hole (neutron-neutron-hole) states. This selectivity arises because the π^{+}-$p(\pi^{-}$-$n)$ elastic cross section is nine times larger than the π^{+}-$n(\pi^{-}$-$p)$ elastic cross section. Thus, measurements of π^{+} and π^{-} inelastic scattering cross sections from self-conjugate nuclei have been used successfully to determine charge-symmetry breaking (CSB) or, equivalently, isospin-mixing matrix elements between bound or quasi-bound states. For example, π^{+}/π^{-} asymmetries observed in ^{12}C(π,π') (Refs. 2 and 3) and ^{16}O(π,π') (Ref. 4) have yielded CSB matrix elements ≤ 200 keV consistent with those expected from the Coulomb force.[5-8]

Strong isospin mixing was hypothesized to explain the large cross section ratio $R_{\gamma}=\sigma(\gamma,p)/\sigma(\gamma,n)$ of up to 2.0 measured in the giant dipole resonance (GDR) region of ^{4}He (24–30 MeV in excitation energy).[9] Consequently, pion inelastic scattering from ^{4}He has been studied[10] in order to obtain a new measurement of the isospin mixing among excited states in ^{4}He. Only small differences in π^{+} and π^{-} cross sections, of the order of those expected from the Coulomb force, were observed and successfully reproduced by distorted-wave impulse approximation (DWIA) calculations using transition densities from the recoil corrected continuum shell model[11] which includes only the Coulomb force as a CSB force. The pion results have cast doubt on the interpretation of the photonuclear ratio as being due to isospin mixing. Indeed, recent ^{4}He$(e,e'x)$ coincidence data[12] and a new value of R_{γ} based on the remeasurement of the ^{3}H$(p,\gamma)^{4}$He cross section[13] are completely consistent with the presence of no CSB force in excess of the Coulomb force.

The sensitivity of the inclusive pion scattering to isospin mixing may be reduced in reactions to the nuclear continuum, if the reactions are dominated by quasifree scattering. Quasifree scattering would yield $R_{\pi}=\sigma(\pi^{+})/\sigma(\pi^{-})\approx 1.0$, the same as for inelastic scattering to states of good isospin. In contrast, exclusive $(\pi,\pi'p)$ experiments would yield $R_{\pi p}=\sigma(\pi^{+},\pi^{+\prime}p)/\sigma(\pi^{-},\pi^{-\prime}p)\approx 9$ if quasifree scattering dominates, and $R_{\pi p}=1$ if states of good isospin are excited. Previous studies of the exclusive $(\pi,\pi'p)$ reaction in the quasifree region have measured $R_{\pi p}$ near the free π-p value.[14] Angular distributions of the ^{4}He$(\pi^{+},\pi^{+\prime}p)^{3}$H reaction at $T_{\pi}=110$ and 162 MeV (Ref. 15) displayed shapes similar to those from free π-p scattering. For the scattering angles ($\theta_{\pi'}=30°$ and 40°) in the (π,π') experiment of Ref. 10 at $T_{\pi}=180$ MeV, the centroid of the quasifree peak is predicted to be below the ^{4}He breakup threshold. Only the tail of the quasifree peak contributes to the ^{4}He continuum region where states are known to exist. Therefore a study of the relative importance of resonance and quasifree scattering is of interest and a ^{4}He$(\pi^{\pm},\pi^{\pm\prime}p)$ coincidence experiment was done to clarify the (π,π') reaction mechanism.

We measured ^{4}He$(\pi^{\pm},\pi^{\pm\prime}p)$ exclusive spectra and extracted angular correlation functions using the Energetic Pion Channel and Spectrometer (EPICS) at the Clinton P. Anderson Meson Physics Facility (LAMPF). The spectra cover the ^{4}He excitation energies between 21.5 and 44 MeV which comprises the relatively narrow 2^-, $T=0$ state at 22.1 MeV and a broad continuum of 2^-, $T=1$, 1^-, $T=1$ and $T=0$, and 2^+, $T=0$ states.[16] The ratio $R_{\pi p}$ of the $(\pi^+,\pi^{+\prime}p)$ to $(\pi^-,\pi^{-\prime}p)$ cross sections has a dramatic dependence on the proton emission angle θ_p. This observation can be explained neither by inelastic transitions to states in ^{4}He (as assumed in the qualitative discussion of Ref. 10) nor by a purely quasifree scattering process. We propose to interpret the strong θ_p dependence as an interference effect.

The scattered pion's momentum was measured using the EPICS (Ref. 17) spectrometer, and the decay protons were detected with eight plastic scintillation detectors mounted in the evacuated scattering chamber. With EPICS positioned to the left-hand side of the beam at $\theta_{\pi'}=30°$, 40°, 60°, and 80°, five of the proton detectors were placed to the right-hand side of the beam at $\theta_p=-30°$, $-45°$, $-60°$, $-75°$, and $-90°$. The remaining three were set at $\theta_p=90°$, 105°, and 120°. Each of the eight proton detectors had a solid angle of 57 msr. The target was ^{4}He gas, contained in a cylindrical flask of 12.7 cm diameter with 25-μm-thick stainless steel walls, cooled to a temperature of 50 K at a pressure of 1.5 bar. The target thickness, gas cell walls, and entrance foil to the scintillators combined to give an energy threshold for decay protons from the center of the target of about 4 MeV. At most pion angles this implied an experimental cutoff in the excitation energy spectra below about 21.5 MeV for the proton detectors to the right-hand side of the beam and below about 30 MeV for detectors to the left-hand side. The pion flux was $\approx 4\times10^7$/sec for π^+ and π^-. The data were normalized to previously measured ^{4}He elastic cross sections.[18] The pulse height in the recoil detectors measured the energy of the decay particle, and this information was combined with the particle's time of flight with respect to pions detected in the spectrometer to identify the decay particle. Also, by calculating the missing mass in the recoil system, protons from the $p+t$ channel were separated cleanly from particles created from the other decay channels, i.e., $d+d$, $p+d+n$, and $p+p+n+n$.

Spectra for protons from the $p+t$ channel are presented in Fig. 1 as a function of excitation energy in the ^{4}He* system for incident π^+ and π^- at $\theta_{\pi'}=30°$ (near the maximum of the differential cross section for the GDR). These spectra are averaged over the five "forward" recoil detectors. Their most striking feature is that $R_{\pi p}=1.5\pm0.5$ for the 2^-, $T=0$ state at 22.1 MeV, but $R_{\pi p}=15\pm4$ for an excitation energy bite summed from 28 to 35 MeV (near the centroid of the GDR). Angular correlation functions were extracted for several excitation energy regions. The double-differential cross sections were transformed to the c.m. system of ^{4}He* and are plotted in Fig. 2 for the $25.0<E_x<30.0$ MeV and the $30.0\le E_x\le 40.0$ MeV regions as functions of $\theta_p^{\text{c.m.}}$, the proton emission angle in the c.m. system of ^{4}He*. In the latter region recoil protons were detected near the quasifree angle *and* in the opposite direction.

We have attempted to interpret the data using the DWIA code 3D.[19,20] In 3D the ^{4}He$(\pi,\pi'p)^3$H reaction is treated as a pion-induced quasifree proton knockout using a factorization approximation. It provides for distortions in the incident pion, the outgoing pion, and the emitted proton waves. For the bound single-particle wave function a parametrization[21] of the nucleon-trinucleon overlap function which includes meson exchange effects was used. A spectroscopic factor $C^2S=2$ was assumed for the knockout of a $0s_{1/2}$ proton in ^{4}He. The final-energy prescription[20] was used to determine the π-p relative center-of-mass energy for evaluating the π-p cross section which were determined by the phase shifts of Rowe, Soloman, and Landau.[22]

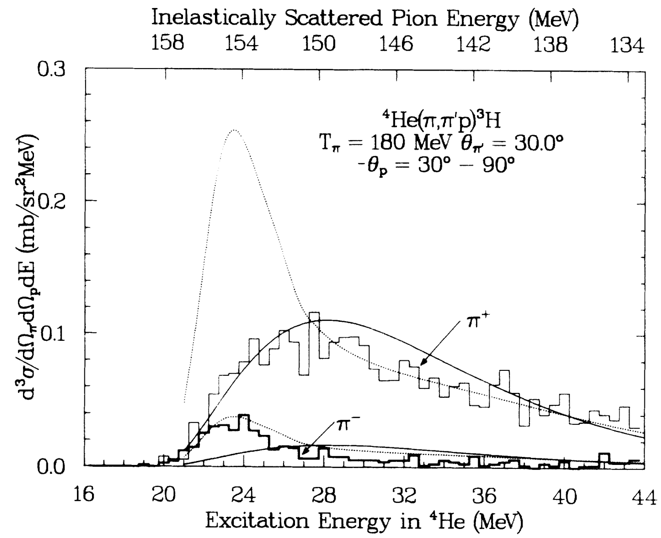

FIG. 1. Exclusive ^{4}He$(\pi^\pm,\pi^{\pm\prime}p)^3$H spectra measured at $\theta_{\pi'}=30°$ and $T_\pi=180$ MeV, averaged over five proton detectors at $\theta_p=-30°$, $-45°$, $-60°$, $-75°$, and $-90°$. The solid and dotted curves are the results of DWIA calculations with two different $p+t$ optical potential parameterizations. The upper two curves are for π^+, the lower two for π^-.

The results of the 3D calculations at $\theta_{\pi'}=30°$ are shown as functions of ^{4}He excitation energy in Fig. 1. The dotted lines are calculations using smoothly energy dependent real and imaginary depths for a $p+t$ optical potential deduced from the work of Ref. 22 on $p+{}^3$He elastic scattering. The solid lines are calculations using the optical potential[23] at $T_p=30$ MeV at all excitation energies. The former potential contains a potential resonance in the $l=1$ partial wave which gives rise to the enhanced cross section below 5 MeV in the $p+t$ c.m. system. In the latter potential the resonance broadens and moves up in energy, and the calculations fit the π^+ data much better. (Because the π^+/π^- amplitude ratio in free pion-proton scattering is about three, the quasifree amplitude for proton knockout is stronger for π^+ than for π^-.) We believe that the better fit to the π^- data with the former potential is accidental since the treatment of resonances only in the $p+t$ channel in the distortions, as done in 3D, is insufficient in π^- scattering for the relatively long-lived 2^- state. The absolute cross sections were found to depend also on the π-^{4}He optical potential. The b_0 and b_1 parameters of the Kisslinger potential were adjusted to give good fits to the elastic $\pi+{}^4$He data below

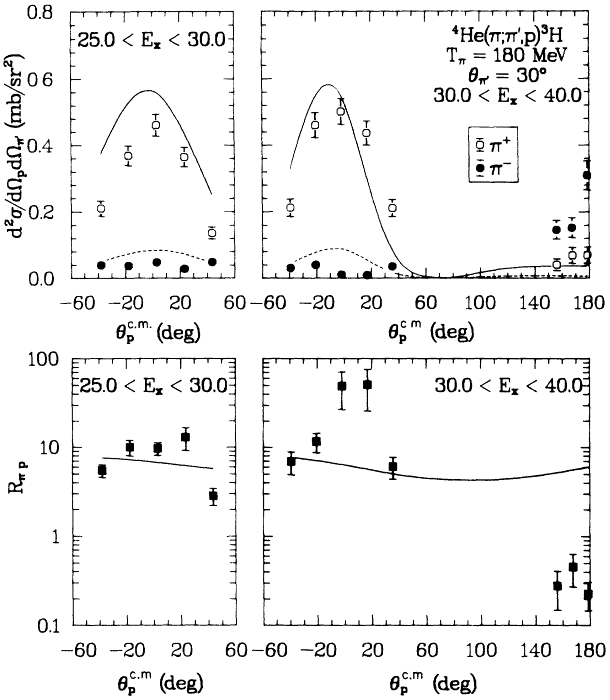

FIG. 2. Top: Angular correlation functions for ^{4}He($\pi,\pi'p$) at $\theta_{\pi'}=30°$ and $T_\pi=180$ MeV summed over $25.0<E_x<30.0$ MeV (left-hand side) and $30.0<E_x<40.0$ MeV (right-hand side). The solid (dashed) lines are DWIA predictions for $\pi^+(\pi^-)$ assuming quasi-free proton knockout. Bottom: The ratio $R_{\pi p}=\sigma(\pi^+,\pi^{+\prime}p)/\sigma(\pi^-,\pi^{-\prime}p)$ of the double differential cross sections plotted in top of the figure. The solid line is $R_{\pi p}$ for the DWIA predictions assuming quasi-free proton knockout.

$\theta_{\rm lab}=80°$. Use of another set, which fits the pion elastic data equally well, approximately doubled the calculated cross sections shown in Fig. 1. However, the ratio between π^+ and π^- predicted cross sections was found to vary minimally when different pion and proton optical potentials were used.

The π^+ angular correlation data and the 3D calculations agree in shape (Fig. 2, top). The agreement in magnitude may be accidental, since the predicted absolute cross section depends sensitively on the distortions. For the $25.0<E_x<30.0$ MeV region, the π^- data display a flat angular correlation near $\theta_p^{\rm c.m.}=0°$ in contrast to the peak in the calculations. In addition, the calculations yield $R_{\pi p}\approx 6$ with a small angular dependence, but the experimental $R_{\pi p}$ varies between 3 and 12 (Fig. 2, bottom left). Even more dramatic are the discrepancies between experiment and quasifree predictions in the $30.0<E_x<40.0$ MeV region. Again the π^+ data are well reproduced, but the π^- data show a minimum in the direction of the quasifree knockout and a maximum in the opposite direction. The experimental ratio $R_{\pi p}$ varies from 45 ± 20 near $\theta_p^{\rm c.m.}=0°$ to 0.22 ± 0.08 near $\theta_p^{\rm c.m.}=180°$ (Fig. 2, bottom). This result is in striking contrast to the predicted values of ≈ 6 at both angles for the quasifree process, and the value of one for scattering through states of good spin and isospin. The strong observed angular dependence of $R_{\pi p}$ suggests an interference of at least two reaction amplitudes. We propose that one of them is the π-induced quasifree proton knockout amplitude and that the formation and decay of states in ^{4}He contributes another.

A third possible interfering amplitude would be from proton knockout by a Δ as it propagates through the nuclear medium.[24] This mechanism was proposed to explain the large values of $R_{\pi p}$ observed[25] in the ^{16}O($\pi,\pi'p$)^{15}N(g.s.) reaction at $T_\pi=240$ MeV, $\theta_{\pi'}=35°$, and $\theta_p=61°$. Kyle *et al.*[25] concentrated on measurements at large values of momentum transfer q and E_x, where states in ^{16}O can be neglected. Thus far, detailed Δ-hole calculations[26] have not fully explained the experimental results. The spectra presented in this Rapid Communication were obtained at values of q and E_x where only the tail of the quasifree peak is expected to contribute and states are known to exist. Therefore, a description of the reaction mechanisms in the ^{4}He continuum must include the possibility of forming states.

Since the 1^- and 2^+ states in ^{4}He are broad and short lived, the time scale of their decay is similar to that for quasifree scattering and interference of these two processes is possible. The π^- cross sections would exhibit the largest effects, since the π^+ and π^- amplitudes for the formation and decay of ^{4}He states should be identical while the quasifree amplitude for π^+ is about three times larger than for π^-.

In contrast to the situation in the GDR region, $R_{\pi p}=1.5\pm 0.5$ is found in the region where the 2^-, $T=0$ state is known to exist. The 2^-, $T=0$ state is a relatively long-lived state, thus a state of good isospin could form and $R_{\pi p}\approx 1$ is expected. The observed rise of $R_{\pi p}$ above one for $E_x\gtrsim 23$ MeV may be due to the tail of the much broader 1^- states. The value of $R_{\pi p}$ between 1 and 2 in this energy region is also seen at $\theta_{\pi'}=40°$ and 60°, where the spectra show a distinct peak near 22 MeV.[27] We note that the recoil corrected continuum shell model calculations predict the dominance of the 2^- excitation near 22 MeV while reproducing the inclusive spectra.[10]

In summary, we have measured cross sections for the reactions ^{4}He($\pi^\pm,\pi^{\pm\prime}p$)^{3}H, and have observed dramatic differences between ($\pi^+,\pi^{+\prime}p$) and ($\pi^-,\pi^{-\prime}p$) in the continuum of ^{4}He states, which includes the GDR. The differences depend strongly on excitation energy and correlation angle. We suggest that this behavior may arise from interference between two or three reaction amplitudes: quasifree ($\pi,\pi'p$) scattering, the formation and decay of resonance states in ^{4}He, and proton knockout by the intermediate Δ. A complete description of the experimental data would require a theoretical approach that treats the different processes consistently within the framework of a model of the nuclear continuum and the pion-nucleus interaction.

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