# Observation of the Quasifree Reactions $^{12}C(\pi^{\pm}, \pi^{\pm}p)$ at 245 MeV

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The inclusive reactions $^{12}C(\pi^{\pm}, \pi^{\pm}p)$ were studied at 245 MeV over a broad kinematic range by coincidence measurement of the outgoing particles. The $\pi^{\pm}$-$p$ angular correlations, proton energy spectra, and the ratio of positive- to negative-pion cross sections are all consistent with those expected from quasifree scattering. For positive pions, quasifree scattering accounts for $(30 \pm 3)\%$ of the inclusive pion inelastic scattering to backward angles. The rest is attributed to the $(\pi^+, \pi^+ n)$ reaction and to multistep processes.

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The pion-induced knockout reaction has attracted much interest because of its important role in pion-nucleus interactions and its potential applications in nuclear structure research. Radioactivity studies of the reactions $^{12}C(\pi^{\pm}, \pi N)^{11}C$ have shown[1] that the ratio of cross sections for $\pi^+$- and $\pi^-$-induced reactions deviates strongly from both the ratio for free pion-nucleon scattering and the expected ratio from plane-wave impulse-approximation calculations. These results indicate that processes other than simple quasifree scattering take place, and they have been interpreted[2,3] in terms of nucleon charge exchange in the final-state interaction. Measurements of the angular distribution and energy spectra of inelastically scattered pions[4-6] indicate that quasifree processes dominate pion inelastic scattering to backward angles. Some pion-proton coincidence measurements have been made,[7,8] but the limited kinematic range covered by these experiments is insufficient to determine the role of quasifree scattering.

We report results of an experiment designed to measure cross sections for quasifree knockout reactions on $^{12}C$ at 245 MeV. The experiment was performed at the $\pi M3$ channel of the Schweizerisches Institut für Nuklearforschung accelerator. Cross sections and energy spectra of protons in coincidence with scattered positive and negative pions were measured. The scattered pions were detected by three telescopes, each of which consisted of two $5 \times 5 \times 5$-cm$^3$ cubes of plastic scintillator with 5-mm-thick scintillators in front and back of the cubes. The front surfaces of the telescopes were 50 cm from the target and their centers were separated from each other by 10°. Energy-loss measurements identified pions over the whole energy region, but their energy spectrum was not measured.

The coincident protons were detected with an array of sixteen scintillators, each $5 \times 10 \times 100$ cm$^3$, arranged in two layers to cover an area of $0.8 \times 1$ m$^2$, with the front surfaces 111 cm from the target. In addition, a 1-mm-thick scintillator was placed in front of the array. Pulse-height and time-of-flight information was recorded for each scintillator, with the time difference between pulses in the phototubes mounted at the ends of each scintillator giving the vertical position of the detected particle. The information was sufficient to identify protons and to measure their energy with moderate resolution. The pion beam was monitored by two thin plastic scintillators mounted on the beam axis and a collimating scintillator with a $5\times5$-$cm^2$ hole, in which the target was mounted. Protons present in the beam were eliminated by degraders in the transport channel and muon and electron contaminations were measured by time of flight.

Calibration measurements were made with a $CH_2$ target. Free $\pi^+$-$p$ scattering was detected in coincidence at several angles to provide proton-energy calibration and checks on the absolute-cross-section measurements. The overall energy resolution measured with the $CH_2$ target, including kinematic broadening, energy losses, and electronics, was 18 MeV. The proton angular resolution was 5° in the horizontal plane and 4° in the vertical plane. The low-energy cutoff for proton detection was 30 MeV. Pions were detected in the angular range of 70°–140° in steps of 10°. The proton-detector array could be moved so that protons could be measured from 140° to 30° relative to the beam direction, covering simultaneously a vertical angular range $-21° \leq \varphi \leq 21°$. For each pion detection angle, protons were detected over an angular range of at least 100° for $\pi^+$ and 80° for $\pi^-$, centered around the angle for free pion-proton scattering. Measurements without target were taken to determine the background.

Figure 1 shows the angular correlation between the pions (detected at a fixed angle) and the protons, for both positive and negative incident pions. The data are presented for the reaction plane ($\Delta\varphi = \pm 6°$) and integrated over the outgoing pion and proton energies. The out-of-plane angular correlation is the same. The errors shown are relative, and contain statistical and angle-dependent systematic uncertainties. There is an additional overall normalization uncertainty of 8%. These curves, and those obtained for all the other pion scattering angles, show a strong peak centered near the angle for free pion-nucleon scattering, superimposed on a low "background." A proton-energy spectrum measured at the peak of the angular correlation curve is shown in Fig. 2. Again, a peak centered near the energy corresponding to free $\pi$-$p$ scattering can be seen. The width of the peak, adjusted for experimental energy resolution is $37 \pm 3$ MeV for $\pi^+$ scattering and $50 \pm 10$ MeV for $\pi^-$ scattering (full width at half maximum). The energy spectrum at angles away from the angular correlation peak is somewhat shifted in peak position and somewhat broader, but always falls off to very low values, well above the experimental cutoff energy. We can therefore conclude that the shape of the angular correlation is not appreciably affected by this

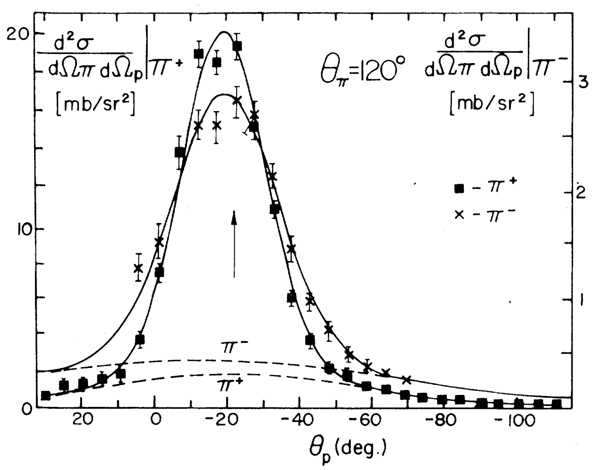


FIG. 1. Pion-proton angular correlations for positive (squares) and negative (crosses) pions detected at 120°. The scale for $\pi^-$ scattering (right-hand side) is that for $\pi^+$ scattering (left-hand side) multiplied by the ratio of free $\pi^-p$ to $\pi^+p$ scattering cross sections. The solid curves are the results of Gaussian fits to the data. The arrow marks the angle for free $\pi N$ scattering.

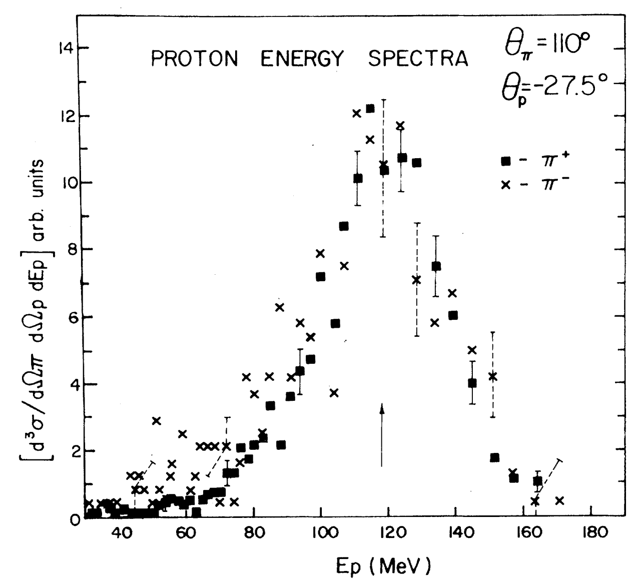


FIG. 2. Energy spectra of protons detected in coincidence with positive (squares) and negative (crosses) pions scattered at 110°. The arrow marks the angle for free $\pi N$ scattering.

cutoff.

Each pion-proton angular correlation was fitted by a least-squares method by a sum of two Gaussian curves whose peak positions, amplitudes, and widths were treated as free parameters. The solid curves in Fig. 1 show the result. We obtain, for all cases, one narrow and one broad Gaussian. The peak of the narrow Gaussian curve lies near the angle corresponding to free $\pi$-$p$ scattering. The standard deviation of the narrow Gaussian is consistent with the Fermi momentum of a proton in carbon. The broad Gaussian component (shown by dashed curves in Fig. 1) has a standard deviation of about 40° for all the measured angular correlations. As can be observed in Fig. 1, the broad Gaussian for $\pi^-$ scattering is relatively higher than that for $\pi^+$ scattering.

These results indicate that we may associate the narrow Gaussian component in the angular correlation with quasifree pion-proton scattering, while the broad Gaussian represents the effects of pion multiple scattering and of nucleon final-state interactions. The relative contribution from pion multiple scattering is expected to be similar for $\pi^+$ and $\pi^-$. The component which corresponds to nucleon final-state interaction is expected to be larger for $\pi^-$ because of a contribution from the $(\pi^-, \pi^- n)$ reaction followed by a nucleon charge exchange, a process which is expected to be relatively small for $\pi^+$. It is not surprising, therefore, that differences between the angular correlations and energy spectra for $\pi^+$ and $\pi^-$ can be observed.

The inclusive $^{12}C(\pi^+, \pi^+)$ cross section at the same bombarding energy, 245 MeV, was previously measured.[5] In order to determine the contribution to this cross section from the quasifree reaction $^{12}C(\pi^+, \pi^+ p)$, we integrated the area under the narrow Gaussian component in the pion-proton angular correlation, including the data obtained outside the reaction plane, and found that over the angular range of $90° \leq \theta_\pi \leq 140°$ this contribution is $(30 \pm 3)\%$. Apart from a small contribution from the quasifree $(\pi^+, \pi^+ n)$ reaction the rest is attributed to pion multiple scattering and to nucleon-nucleus final-state interactions. The separation of the contributions from each of the latter two processes requires a better understanding of at least one of them.[9]

The results of the integrations of the quasifree scattering are shown in Fig. 3(a) as a function of $\theta_\pi$ for both positive and negative pions (the scale for the latter is multiplied arbitrarily by 10). The solid curve represents the results of free

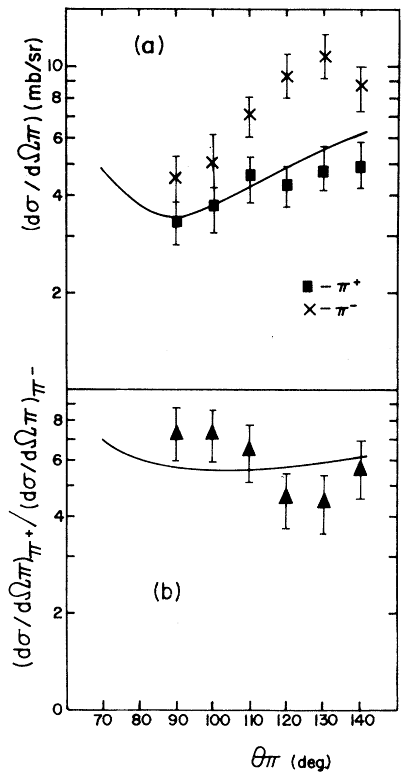


FIG. 3. (a) Angular distributions of quasifree $^{12}C(\pi^+,\pi^+ p)$ (squares) and $^{12}C(\pi^-,\pi^- p)$ (crosses, multiplied by 10). The curve is the angular distribution for free $\pi^+ p$ scattering. (b) Ratios of the quasifree $\pi^+$ to $\pi^-$ cross sections. The curve is the free $\pi^+ p$ to $\pi^- p$ cross-section ratio.

pion-proton scattering,[10] showing a good agreement. Figure 3(b) shows the cross-section ratio of the quasifree $(\pi^+, \pi^+ p)$ to $(\pi^-, \pi^- p)$ scattering compared with the ratio for free pion-nucleon scattering, and again the agreement is good. These results give further support to the way we identify the quasifree process and can explain why the observed ratios are so different in experiments which are not selectively sensitive to quasifree scattering such as radioactivity studies.

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