Inclusive Pion Scattering in the (3,3) Resonance Region

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Energy spectra from π^+ inelastic scattering on ^{4}He, ^{12}C, ^{58}Ni, and ^{208}Pb have been measured at $T_\pi = 100$, 160, and 220 MeV. These spectra have prominent features which are qualitatively consistent with quasifree scattering from nucleons. For ^{4}He at low energies, true absorption becomes the dominant fraction of the reaction cross section, and inelastic scattering is strongly inhibited. This is in marked contrast to the behavior of the partial reaction cross sections for the other nuclei.

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Progress in understanding the fundamental dynamics of pion-nucleus reactions has been hampered by a lack of experimental information on rather simple, macroscopic features of the reaction process. In this Letter we report the measurement of inclusive pion spectra from pion-induced reactions on ^{4}He, ^{12}C, ^{58}Ni, and ^{208}Pb. The importance of these data lies in the fact that the distributions in energy loss and momentum transfer of the scattered pions provide a crucial link in understanding the competing reaction modes of elastic scattering, inelastic "quasifree" scattering which is modeled by scattering from single nucleons, and more complex inelastic modes involving more than one nucleon. Hitherto such distributions were only available for pion charge-exchange reactions and in low-resolution nuclear emulsion experiments.[1-3] Previous published studies with high-resolution devices were generally limited to one nucleus or to a small number of angles.[4,5] A complete report on our measurement along with tabulations of the data will be presented in a future publication. Here we concentrate on the general features of the data and in particular on the comparison between the different nuclei. Our results show that true pion absorption (where no pion is present in the outgoing channel) is much more important in the reactions on ^{4}He at the lowest energy than on the other targets. This seems to be the only case where the structure of the target nucleus is important in determining the simple macroscopic features of the reaction.

The experiment was performed on the pion and particle physics channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). Positive pion beams with kinetic energies of 100, 160, and 220 MeV were focused in a 1×2-cm^2 spot onto solid samples of ^{12}C (0.39 g/cm^2), ^{58}Ni (0.60 g/cm^2), and ^{208}Pb (0.57 g/cm^2), and a liquid-^{4}He target (described in detail in Ref. 6). Pions were detected in the large acceptance spectrometer (LAS) developed for this measurement by the present experimental group. A detailed description of the spectrometer and the algorithm used to obtain target coordinates and pion momenta is given in Ref. 7. Briefly, LAS consists of a quadrupole doublet followed by a dipole bending magnet with a 45° bend for the central trajectory. In the present experiment, a relatively small solid angle (~15 msr) and momentum acceptance (±10%) were employed to reduce uncertainties from the spectrometer acceptance function.

The relative pion flux on target was monitored in an ionization chamber positioned immediately upstream of the target. The known target thicknesses were used to obtain the absolute normalization relative to π^+-p scattering measured at each scattering angle with a CH_2 target. A C_8H_8 (styrofoam) target with dimensions identical to that of the ^{4}He target served as the hydrogen target for the ^{4}He normalization. Pion-nucleon cross sections were calculated with use of the phase shifts of Ref. 8. Muons from pion decay were rejected by requiring valid events to follow consistent trajectories in the spectrometer and to project back to target coordinates within the size of the incident pion beam spot. Monte Carlo calculations provide an estimate that these constraints serve to reject more than 97% of the muons from the decay of pions in flight.

Spectra were measured at seven angles on the solid targets (30°, 50°, 70°, 90°, 110°, 130°, and 146°) and five angles on the ^{4}He target (30°, 60°, 90°, 120°, and 146°). Data in four momentum bites were accumulated at each angle at 220 MeV ($T_\pi = 50$ to 230 MeV) and 160 MeV ($T_\pi = 35$ to 170 MeV) while three momentum bites were used at 100 MeV ($T_\pi = 35$ to 110 MeV). The ^{4}He spectra were corrected for average energy loss as a function of detected pion energy in the extended target. These corrections were negligible for the other targets. The background for the ^{4}He measurements was determined by collecting data with the empty cryostat in the target position.

The uncertainty in the relative normalization between regions of the spectra accumulated in different momentum settings and different targets at the same angle was determined to be ± 10% while the uncertainty in the absolute cross sections is estimated to be ± 15%. In order to obtain energy-integrated cross sections the yield of low-energy pions was estimated by extrapolating the cross section linearly to zero for zero-energy pions. The angle-integrated charged pion cross sections which we extract agree within experimental uncertainty with those of Refs. 9, 10, and 11.

Some pion spectra for 160-MeV π^+ incident on ^{4}He are shown in Fig. 1, and for 146° and all four targets in Fig. 2. The striking feature of the spectra in Fig. 2 is their similarity. In fact, except for the elastic peak and incompletely resolved structures seen near the elastic peak at forward angles which presumably are due to inelastic scattering to discrete nuclear levels, there is little to distinguish the spectra of ^{12}C from ^{58}Ni or ^{208}Pb. This indicates that the reaction mechanism is dominated by a common mechanism which does not depend on the detailed structure of the target. At every angle, each spectrum contains a peak at an energy near to that appropriate for the scattering from a free nucleon (denoted by the arrows in Figs. 1 and 2), which suggests a quasifree scattering reaction

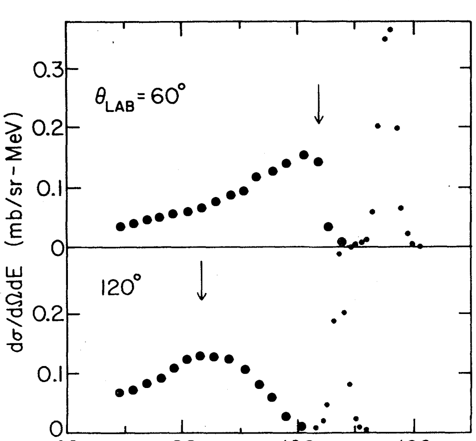

FIG. 1. Energy spectra of 160-MeV π^+ scattered by ^{4}He to $\theta_{lab} = 60°$ and 120°. The arrows denote the energy of elastically scattered 160-MeV pions from free nucleons.

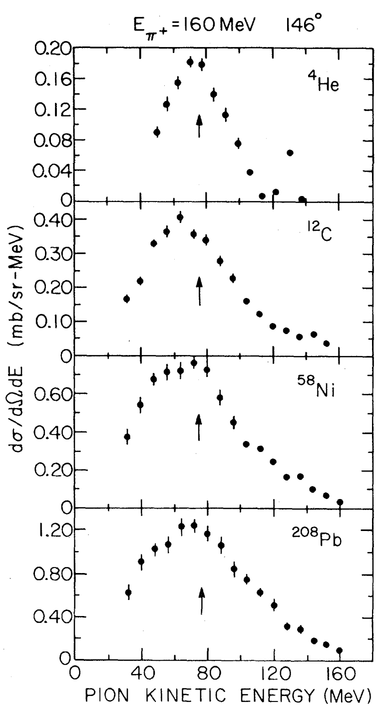

FIG. 2. Energy spectra of 160-MeV π^+ scattered by ^{4}He, ^{12}C, ^{58}Ni, and ^{208}Pb to $\theta_{lab} = 146°$. The arrows have the same meaning as in Fig. 1.

mechanism. Similar effects have been noted in pion charge-exchange reactions, especially at back angles.[1] In the present results, however, the observation of the quasifree peak persists at forward angles. Still, the quasifree mechanism cannot account for all the features of the energy spectra. In forward-angle pion scattering, quasifree scattering cannot explain the sizable yield of low-energy pions. In backward-angle pion scattering, experiments[11] indicate that only a fraction (50%–70%) of the forward-angle protons expected from the back-angle pion yields are present. For comparison, while the scattering of a weakly interacting particle, such as an electron, is dominated by quasifree scattering,[12] the scattering of medium-energy protons (~150 MeV) does not show a quasifree peak except at very forward angles.[13] In contrast to proton scattering at lower (E_p = 90 MeV)[14] and higher (E_p = 800 MeV)[15] energies a single-collision model fails to predict the scattered-proton momentum spectrum. Evidently a more complicated mechanism is indicated for the proton reactions at comparable momentum transfer even though the *NN* total cross section is considerably smaller than the πN total cross section. In some sense it is surprising that pion quasifree scattering features are evident at all in light of the large pion-absorption cross sections. It seems plausible that true absorption actually enhances the quasifree aspects of the pion spectra by limiting scattering interactions to the nuclear surface.

The ^{4}He spectra reveal qualitative differences between pion scattering from ^{4}He and the other targets. We note that to the extent that the scattering is quasifree, it is more appropriate to compare cross sections in the laboratory frame than in the center-of-mass frame. Elastic scattering is stronger relative to inelastic scattering at back angles for the helium target than for the other targets. This is reasonable since the tight binding or equivalently, the small size of ^{4}He, produces a larger elastic form factor at large momentum transfer. These kinematic and structural differences also give rise to target-dependent differences between the energy-integrated angular distributions of the four targets. The ^{4}He angular distributions vary more slowly with angle than do those of the other target nuclei.

In Fig. 3 we show the energy dependence of the ratio of the reaction ($\sigma_R = \sigma_{IN} + \sigma_{ABS}$) and of the inelastic cross sections to the total cross section[16,17] for ^{4}He along with the same quantities

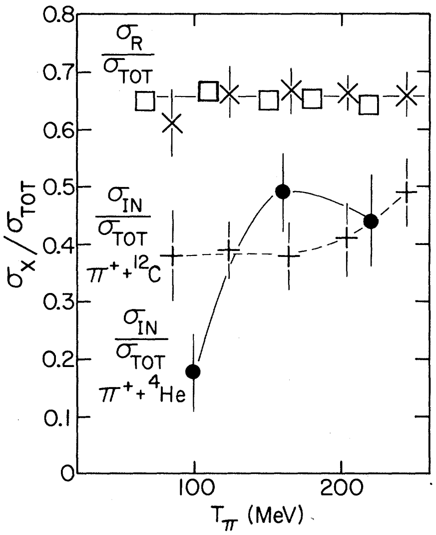

FIG. 3. The ratio of σ_{IN} and σ_R to σ_{TOT} for ^{4}He (circles and squares, respectively). Experimental π^- data and charge independence were used to obtain σ_R/σ_{TOT} (Ref. 17). The same ratios for $\pi^+ + ^{12}$C are shown by the plusses and crosses, respectively. The lines are drawn to guide the eye.

for ^{12}C.[9] The inelastic yield includes an estimate of the charge-exchange cross sections by scaling the measured charged-pion cross sections with the ratio

$$\sigma_{\pi^- p \to \pi^0 n}/(\sigma_{\pi^+ p \to \pi^+ p} + \sigma_{\pi^- p \to \pi^- p})$$

at each energy.[1] The ratio of reaction to total cross section is essentially independent of energy and the same for ^{4}He and ^{12}C. There seems to be no simple explanation for the precise value of this ratio, 0.66. In contrast the energy dependence of σ_{IN}/σ_{TOT} appears to be rather different for ^{4}He and ^{12}C. (The larger uncertainty in the 100-MeV ^{4}He inelastic cross section is the result of the uncertainty in the extrapolation of the yield to low inelastic pion energies.) This implies a corresponding difference in the energy dependence of the absorption cross sections for ^{4}He and ^{12}C with absorption being a much larger fraction of the total cross section for $\pi^+ + ^4$He at 100 MeV. The specific structure of ^{4}He seems to be important in determining the distribution of the reaction cross section into inelastic scattering and absorption, but not in determining the overall fraction of the total cross section composing the reaction cross section. Our results are in disagreement with the recent cloud-chamber work of Balestra *et al.*,[18] but are in reasonable agreement with the early work of

Fowler *et al.*[19]

The data on ^{4}He emphasize the coupling between the inelastic and absorption channels. Hirata, Lenz, and Yazaki[20] have calculated the π-^{4}He partial cross sections within the framework of the isobar-hole model which includes this coupling in the description of the decay of the isobar by reëmission of the pion or by absorption. They adjust the energy dependence of the isobar optical potential to reproduce the experimental elastic and total cross sections, and obtain inelastic scattering and absorption cross sections in reasonable agreement with the present results, particularly with the qualitative feature that the absorption cross section peaks well below the resonance energy. It is interesting that a similar calculation[21] for ^{12}C also predicts that σ_{IN}/σ_{TOT} should decrease at ~100 MeV, in disagreement with the experimental results of Ref. 9.

In conclusion, we have reported the first results of a study of inclusive pion scattering on a variety of targets in the (3,3) resonance region. The pion energy spectra illustrate the importance of quasifree scattering, with some contribution from more complicated processes. In reactions on ^{4}He the quasifrèe mechanism is suppressed at 100 MeV and contrary to the systematics[10] of weaker absorption for smaller-mass targets, absorption dominates. This dependence of the reaction mechanism on the particular nuclear target is an important feature which must be reproduced in any comprehensive model of pion-nucleus reactions.

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