Inclusive Scattering of 500-MeV Pions from Carbon

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Inclusive double-differential cross sections for 500-MeV pions are presented for $C(\pi^{\pm},\pi^{\pm})$ at θ_{lab} of 30°, 40°, 50°, 70°, and 90°; and for $C(\pi^{-},\pi^{-})$ at 110°. We compare the 50° and 70° data with $C(e,e')$ data at nearly the same momentum transfer. These spectra from very different probes are more similar than expected from an intranuclear cascade calculation, which includes the strong rescattering of pions that have energies near 180 MeV. Agreement of the calculated spectra and the pion data is improved if the nucleus is assumed to be nearly transparent to these pions.

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The pion provides several unique aspects as a nuclear probe. Two of these stand out for pions with kinetic energy near 500 MeV. These pions have one of the longest mean free paths (mfp) in nuclear matter among the strongly interacting probes: only the K^+ is more penetrating. Second, pion production can be used to provide two resonance energy pions. Hence 500-MeV incident pions can be used to study the π-nucleon interaction with energies near the $\Delta_{3/2,3/2}$ resonance in the center of the nucleus. Since Δ formation and decay provides the major route for energy transport through hot dense hadronic matter, understanding the transport mechanisms in this energy range will be crucial to the interpretation of current and planned experiments which rely on the measurement of pions as a hadronic signature of a quark-gluon plasma. Additionally the interpretation of electroproduction of baryonic resonances in nuclei will require a thorough understanding of the transport of pions in this energy range. Our initial expectation is that while pions produced at energies above and below the Δ resonance will escape from the nucleus and be observed, those created near 180 MeV will be absorbed or scattered to lower energies. The fact that this expectation is not realized in our spectra is the subject of this Letter.

We present data for the inclusive scattering of 500-MeV charged pions from natural carbon. The measurements were performed at the P^3 pion channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). The scattered pions were detected with the Large Acceptance Spectrometer (LAS) [1], a quadrupole-quadrupole-dipole spectrometer, with its dipole set to provide a nominal 30° vertical bend and the quadrupole fields set to maximize the solid angle of the spectrometer. Four position measurements (2 in X and 2 in Y) were made, immediately before and after the dipole of the spectrometer. The trigger scintillators were located behind the rear wire chambers with one before and one after a threshold gas Cherenkov counter, which was used to eliminate electron events. The trigger was formed by the coincidence of the two scintillators and any one of the four chamber planes before the dipole. Data were taken with two different carbon targets; the areal densities of the two targets were 543 mg/cm^2 and 1.090 g/cm^2. Relative beam normalizations were accomplished with a thin parallel-plate ion chamber located immediately upstream of the scattering chamber. The data were normalized to $^1H(\pi,\pi)$ elastic scattering from a CH_2 target using the cross sections calculated from the phase shifts of Arndt [2]. We estimate the absolute uncertainty in our cross section to be ±10%.

Figure 1 shows inclusive spectra for $C(\pi^{\pm},\pi^{\pm})$ at five angles (30°, 40°, 50°, 70°, and 90°), and $C(\pi^{-},\pi^{-})$ at 110°. The cross sections are plotted as a function of the pion laboratory energy loss, i.e., $T_{\pi}^{in}-T_{\pi}^{out}$. At each angle where there are both (π^{-},π^{-}) and (π^{+},π^{+}) data one sees that the data sets are virtually indistinguishable, as expected by charge symmetry. The forward-angle spectra are dominated by the elastic peak. At a slightly lower outgoing pion energy there is a broad peak that follows the kinematics of elastic scattering from hydrogen, i.e., quasielastic (QE) scattering. The rise in the cross section in each spectrum at lower pion energies (larger energy loss) is believed to be due to pion production (see below).

In Fig. 2 we compare the pion scattering data at 50° and 70° to electron-scattering data at similar momentum transfer. In each case the electron spectrum is shifted so that elastic-electron scattering from carbon occurs at the same energy loss as the pion-elastic scattering. The electron data are normalized to the pion data. This requires an energy shift of 2.7 MeV for the (e,e') data of O'Connell *et al.* [3] (T_e = 730 MeV and θ_{lab} = 37.1°)

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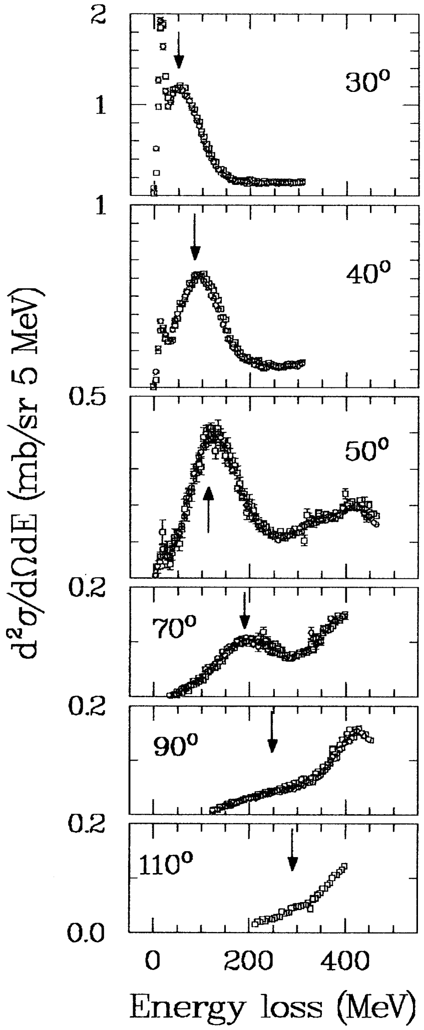

FIG. 1. Inclusive spectra for the scattering of 500-MeV pions from natural carbon at the indicated laboratory angles. The red open circles are (π^+, π^+) and the blue open squares are (π^-, π^-). The arrows indicate the energy loss of elastic scattering from ^{1}H.

when compared with our 50° data. For these kinematic conditions ^{1}H(π, π) has a lab momentum transfer of 488 MeV/c while for ^{1}H(e, e) it is 443 MeV/c. The ratio of the (π, π') doubly differential cross section to the (e, e') cross section at the QE peak is ~3600. The ratio of the free cross sections is 4960. The similarity of the pion and electron spectra even in the "dip" region is remarkable.

The (e, e') data set that we compare to our 70° data in Fig. 2 is from Garino *et al.* [4] (T_e=779.5 MeV and θ_{lab}=50.4°). In this comparison the lab momentum transfers for ^{1}H(π, π) and ^{1}H(e, e) are 624 MeV/c and 610 MeV/c, respectively. The (e, e') data of Garino *et al.* in Fig. 2 are shifted by 2.9 MeV and the ratio of the cross sections, (π, π') to (e, e'), at the QE peak is ~5300.

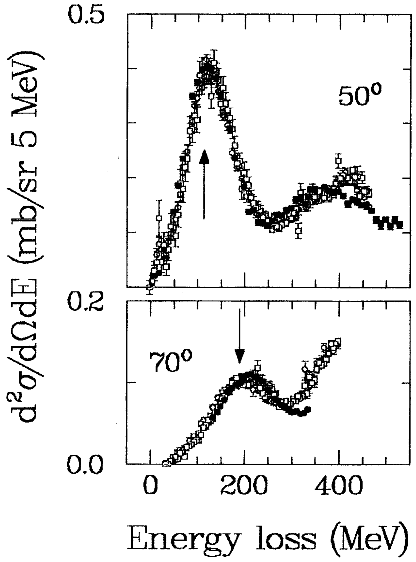

FIG. 2. Comparison of the C(π, π') data at 50° and 70° to C(e, e') data at nearly the same momentum transfer. The red open circles are (π^+, π^+), the blue open squares are (π^-, π^-), and the solid black circles are (e, e'). See text for further discussion.

The free cross section ratio is 5640.

That the ratios of continuum scattering of pions and electrons are so near the ratios of free elastic scattering is remarkable, and indicates that a strongly interacting pion beam has much the same access to the nucleons in carbon as does an electron beam. This would not be anticipated by arguments based on the mfp and absorption of the pions.

Figure 3 shows a comparison of the data with results from a calculation (the blue histograms) using an intranuclear cascade (INC) code [5]. The INC code uses the elementary π-nucleon cross section, and realistic models for pion production. Short range correlations among the spatial coordinates of the nucleons are included according to the Malfliet-Tjon potentials [6]. The INC code does not allow for the coherent recoil of the entire nucleus so it is not suitable for low-momentum transfer reactions such as elastic scattering. The code does, however, predict the location of the QE peak correctly. While the magnitude of the QE peak is slightly overpredicted at forward angles it agrees well with the data at 50° and larger angles. Note also that in the high energy loss (low outgoing pion energy) portion of the $(\pi^\pm, \pi^\pm)$ spectra where pions in the calculation come from pion production there is also good agreement between the data and the INC calculation. This leads us to conclude that the rise in cross section in the high energy loss region of the data is due to $(\pi, 2\pi)$ reactions.

The striking feature in Fig. 3 is the underprediction of cross sections for pions with energy loss between 250

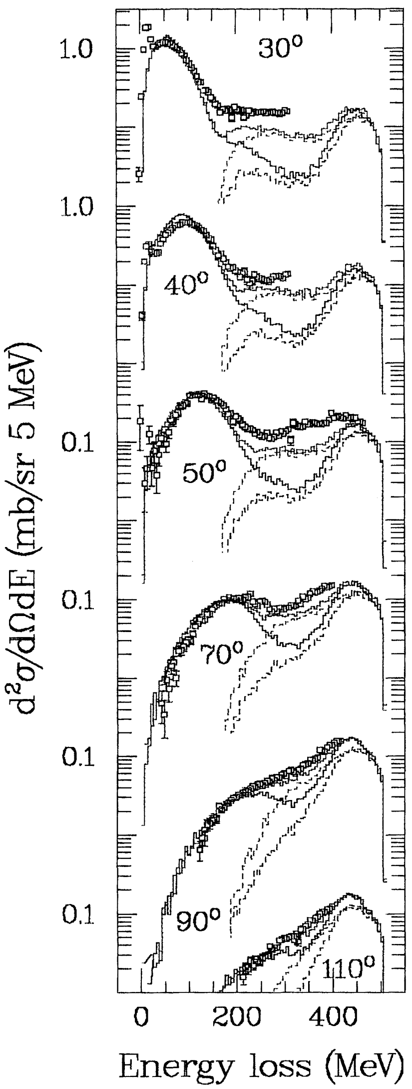

FIG. 3. The (π^-, π^-) data (open circles) is compared with two different intranuclear cascade calculations. The blue histograms are from a calculation where pions from $(\pi, 2\pi)$ reactions have τ_π=0 fm/c, which means that they can interact immediately. In the other calculation (red histograms) pions from $(\pi, 2\pi)$ reactions are assumed not to interact for a time equal to 2 fm/c. The dashed histograms indicate the portion of the respective INC calculations that are due to $(\pi,2\pi)$ reactions.

MeV and 400 MeV, or with laboratory energies near 180 MeV. The low cross section from the INC calculation in the region around 180 MeV of outgoing energy is the result of the short mfp for pions in the resonance region (see Fig. 4). Pions in this region are strongly scattered and therefore are lost in the INC spectrum.

The reason for the marked enhancement of the data for energy losses near 300 MeV relative to the INC calculation in Fig. 3 is not clear. Since the shapes of (π, π') and

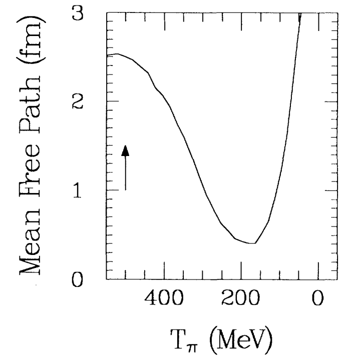

FIG. 4. The calculated pion mean free path (mfp) as a function of kinetic energy. The calculation of the mfp is $1/\rho_0\sigma_{\rm tot}$ where ρ_0 is the central nuclear density and $\sigma_{\rm tot}$ is the isospin-averaged pion total cross section at a given kinetic energy. The arrow indicates the mfp at the pion beam energy in this experiment.

(e, e') spectra are so similar (Fig. 2), one might conjecture that the same mechanism that fills the "dip" region in the (e, e') data fills this region in the (π, π') spectra. In the (e, e') spectra the filling of the dip region is attributed [7] to multinucleon effects. Certainly some of the same effects must be at work in (π, π') spectra. However, before this conclusion is drawn, one needs to consider that there is a fundamental difference between the pion and electron spectra in the dip region. The difference is that the inclusive pion spectra in the dip can include either of the two pions from $(\pi, 2\pi)$ reactions; this mechanism is not present as a contribution to the inclusive electron spectra. Therefore the conjecture that it is the same mechanism that fills the dip in both reactions is not obvious. This realization also makes the striking similarity in the shapes of the pion and electron spectra more puzzling.

Agreement between the data and the INC calculation can be greatly improved if the pions from $(\pi, 2\pi)$ reactions in the INC calculation are prevented from interacting with the nucleus for some period of time (τ_π) after the $(\pi, 2\pi)$ reaction takes place. Figure 3 shows the results of an INC calculation where a value of τ_π of 2 fm/c is assumed for the $(\pi, 2\pi)$ pions. One sees that this INC calculation with nonzero τ_π is much closer to the data at all angles than is the standard INC calculation with τ_π=0 fm/c. Note the special feature with pion-induced pion production using pion beams around 500 MeV (~624 MeV/c)—the incident pion has only a moderate cross section and can penetrate the nucleus, whereas after a $(\pi, 2\pi)$ reaction the pion is in the delta region. Thus the external hadronic system is allowed to enter the nucleus relatively easily but the produced pion, at least in the standard hadronic picture, is lost by multiple nucleonic collisions because of its larger cross section. This absorption or rescattering of pions to lower energy, which is predicted to be a very strong effect, is absent in the present data.

One can imagine various models in which Δ propagation or Δ interactions lead to a coherent transport mechanism which alters the mfp picture of propagation with quantum corrections. While there is no doubt that such corrections are present, calculations indicate that they are small.

As an alternative model for the filling of the dip, we have considered the possibility of the formation of a σ meson. This σ meson corresponds to the bare $q\bar{q}$ state in the spirit of Jennings and Miller's [8] hadronic representation of color transparency in terms of baryon resonances. If the pion-production mechanism is predominately through the formation of a σ, the isospin zero character of the σ would cause it to experience very little interaction since no Δ formation is possible. If the bump that appears in low-energy pion production on hydrogen [9] can be associated with this effect, the "sigma" width would be of the order of 40 MeV or less, and it would have adequate time to leave the nucleus. Thus the production of σ mesons, which subsequently decay to pions, is one mechanism for getting the pions out of the nucleus, specific to the $(\pi, 2\pi)$ reactions.

Two possibilities for future studies with 500-MeV pions would be the measurement of the inclusive (π^+, π^0) and (π^+, π^-) spectra and the measurement of a pair of pions in the final state with at least one of them being a resonant-energy pion. Yet another study is inclusive cross section measurements with higher energy pion beams—if the apparent transparency we observe is restricted to the region of resonant energy pions then higher beam energies should provide larger regions where INC calculations correctly predict the inclusive spectra. One could measure yields of resonant-energy pions in the $(e, e'\pi)$ reaction or the (γ, π) reaction. If the filling of the dip is associated with the presence of resonance energy pions at the central nuclear density, that is with produced pions regardless of the production mechanism, one should see its effect in these reactions. However, if the extra pions are due to "σ-meson production," one might expect to see enhancements in pion-induced reactions but not in pion-electroproduction or -photoproduction reactions.

In conclusion, inclusive pion spectra for 500-MeV pions scattered from carbon are presented which have shapes that are remarkably similar to the inclusive (e, e') spectra at the same momentum transfer. The ratio of the (π, π') to the (e, e') cross sections at the quasielastic peak is within 30% of the free cross section ratio. The (π, π') inclusive spectra at large energy loss, with outgoing pion energies near the Δ resonance, fail to show the depletion in cross section expected from intranuclear cascade Monte Carlo predictions. The assumption of a transparency for pions from $(\pi, 2\pi)$ reactions in nuclear matter removes a great deal of this discrepancy. This comparison of the INC calculations to the data suggests the need for some mechanism that allows resonant-energy pions produced in the nuclear interior to appear outside the nucleus.

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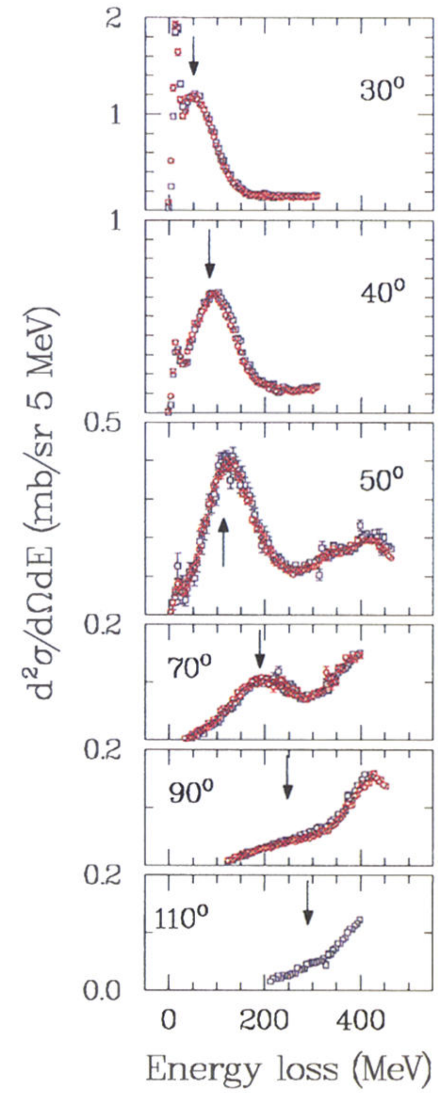

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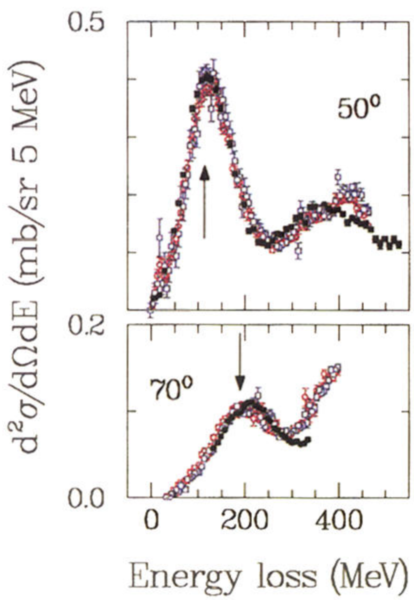

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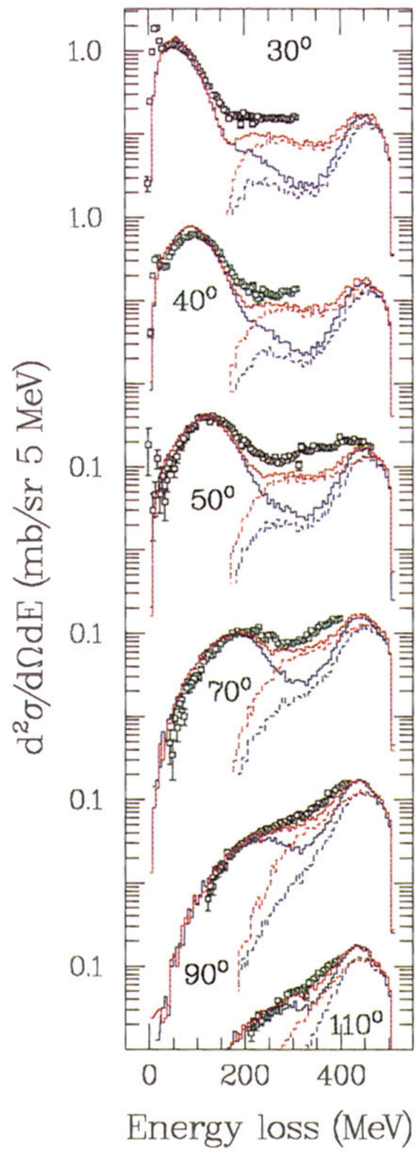

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