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PION SCATTERING AT ENERGIES ABOVE THE Δ RESONANCE*

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The Δ(1232) resonance dominates pion-nucleon scattering at energies below 300 MeV, the region in which pion-nucleus scattering has been well studied using spectrometers at the meson factories. Above this energy region few pion-nucleus scattering data exist. Recently, spectrometers at Brookhaven, LAMPF, KEK, and DUBNA have been used to obtain initial data for pion-nucleus scattering in this energy region. In this talk, we review some data that have been obtained using the LAS spectrometer at LAMPF.

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1. Introduction

Several years ago, we modified the LAS spectrometer and developed a dispersed beam tune for the P3 channel at LAMPF. This system has obtained better than 2 MeV of energy resolution with a 500-MeV pion beam. With this system, we have pursued a program of elastic scattering, pion double charge exchange, and quasifree scattering at energies above the 3-3 resonance. In this talk, we present some recent results of this study.

2. Elastic scattering

The interest in pion-nucleus scattering above the Δ resonance is driven by the changing nature of π-nucleon scattering as the pion kinetic energy is increased. This is illustrated in Fig. 1, where the energy dependence of

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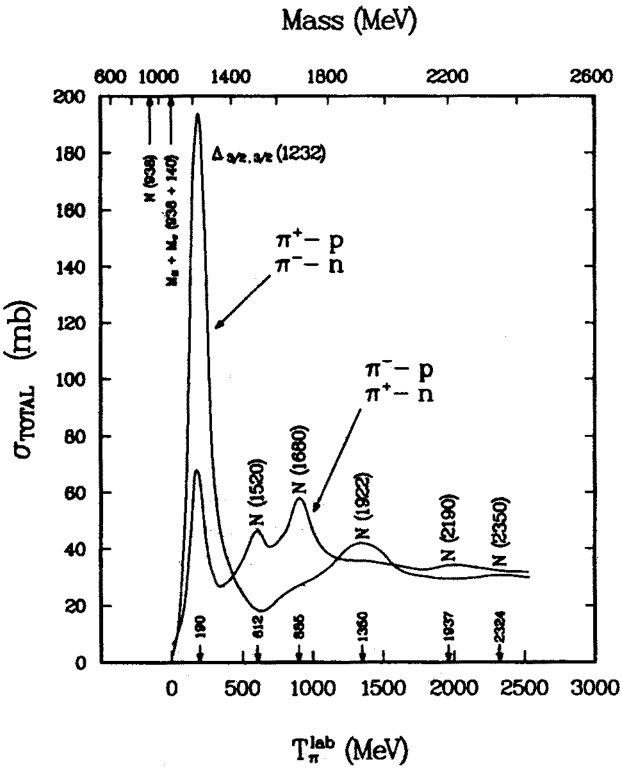


Fig. 1. πN cross section versus pion energy.

the π-N scattering is shown. In the region of the [3-3] resonance, the pion-nucleon cross section reaches the unitary limit. As a consequence, the pion mean-free path in nuclear matter is very short, and pions mainly probe the nuclear surface.

However, above 300 MeV, this situation changes dramatically. The Δ[1232] resonance no longer dominates the scattering. A series of weaker $T = 1/2$ resonances, N^*'s, appears in the spectrum. The isospin-averaged $\pi - N$ cross sections drops from its peak value of 135 mb at $T_\pi = 180$ MeV to a low of 25 mb at 500 MeV. This results in nearly a factor-of-six increase in the pion mean-free path, $\lambda = 1/(\rho\sigma)$ (where ρ is the nuclear density and σ is the isospin averaged cross section) from 0.4 fm to 2.2 fm at 180 MeV and 500 MeV, respectively.

The influence of this change in the mean-free path on elastic scattering can be observed in Fig. 2 where we display cross sections for pion elastic scattering from ^{12}C at energies from 180 MeV to 673 MeV. The 400- and 500-MeV data [3] were obtained using the LAS spectrometer with the P^3-

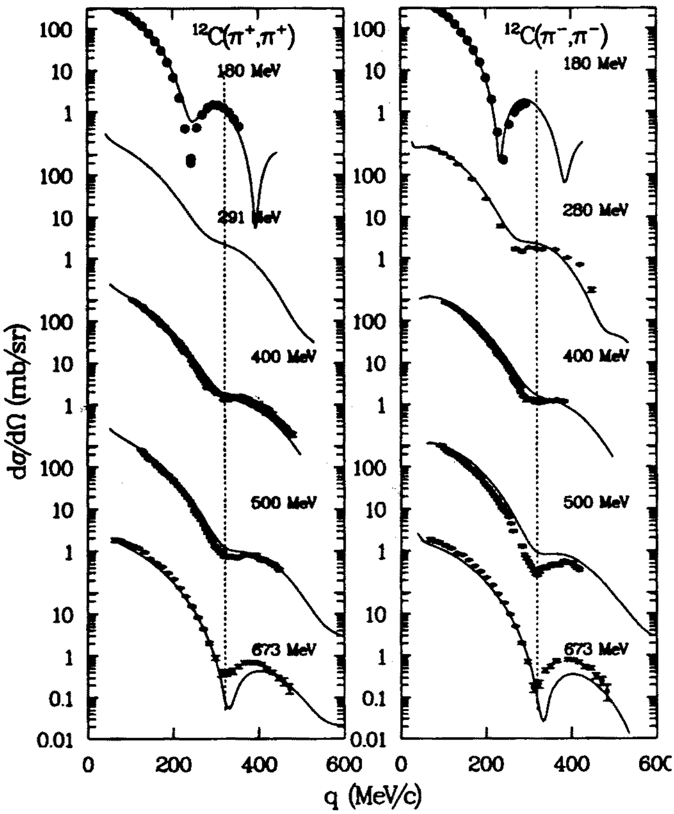
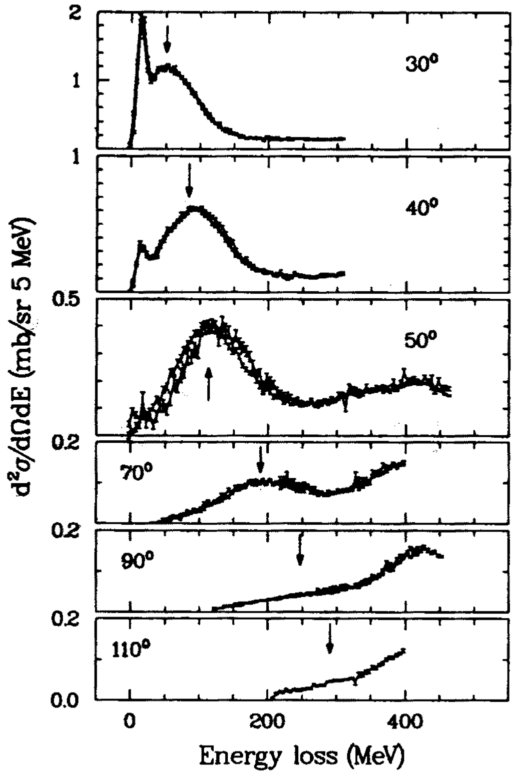


Fig. 2. $^{12}C(\pi,\pi)$ elastic-scattering cross sections versus momentum transfer. The 180-MeV and 280-MeV data are from Ref.[1], the 400-MeV and 500-MeV data are from Ref.[3], and the 673-MeV data are from Ref.[2]. The solid curves are first-order momentum space calculations using the code ROMPIN by Chen, Ernst, and Johnson[4].

East channel at LAMPF. The data are plotted as a function of transverse momentum transfer, $q = 2k\sin(\theta/2)$. For scattering from a black disk of radius R, the cross section is given by

$$\frac{d\sigma}{d\Omega} \sim \left[\frac{J_1(qR)}{qR}\right]^2 . \tag{1}$$

The strong absorption radius, R, can be extracted by setting qR at the first minimum in the data to the value of the first zero of the Bessel function. The first minimum in the angular distributions shown in Fig. 2



CLM_FIG3.MPR

Fig. 3. Inclusive spectra for the scattering of 500-MeV pions incident from natural carbon with the scattered pions measured at the indicated laboratory angles. The open circles are (π^+, π^+) and the open squares are (π^-, π^-). The arrows indicate the energy loss of elastic scattering from ^{1}H.

moves from its lowest value of 235 MeV/c at 180 MeV to 320 MeV/c at 500 MeV. This gives $R = 2.41$ and 1.74 fm at 180 and 500 MeV, respectively. The expected long mean-free path is indeed experimentally observed as a smaller strong absorption radius at energies above the Δ than at resonance energies. This conclusion is supported by the first-order momentum-space calculations using the code ROMPIN by Chen, Ernst, and Johnson [3] shown as solid curves in Fig. 2.

3. Quasi-free scattering

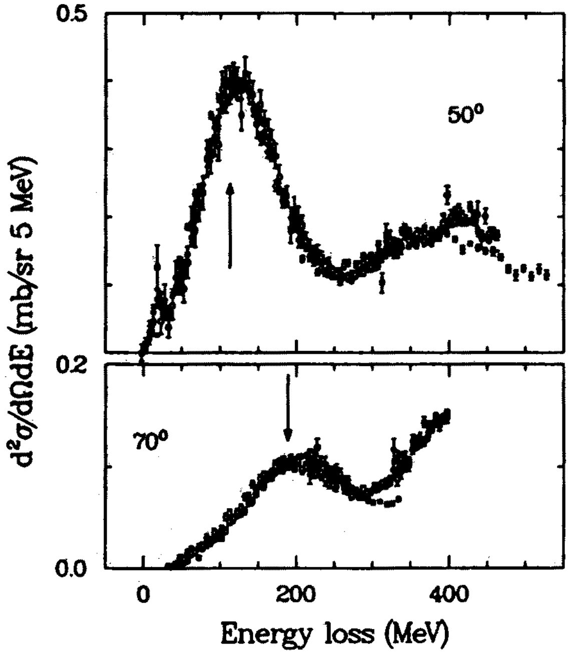
Another large piece of the pion-nucleus total cross section is quasi-free (QF) scattering. This channel contains most of the inelastic cross section. Pions above the [3,3] resonance provide an interesting probe of QF processes because of their already demonstrated long mean-free path and consequent access to the center of the nucleus. In addition to QF scattering, pion production has a large cross section at these energies. Pion production by 500-MeV pions allows resonance-energy pions to be produced in the center of the nucleus and thus allows the study of interaction of these pions at high nuclear density.

Spectra at various scattering angles for inelastic pions scattered from ^{12}C at a beam energy of 500 MeV are shown in Fig. 3 [5]. The data show a peak at the energy loss associated with π–N scattering and a peak at lower energies presumably associated with pion production. This peak at larger missing energies is often called the Δ peak because it is assumed to be due to the QF production of Δ's. It is not clear that this mechanism dominates the pion production in this case. The region between the QF peak and the Δ peak is referred to as the dip region and has been extensively studied in inelastic electron scattering. Many processes are assumed to contribute to the cross section in this region: tails from the Δ region due to Δ–N interactions in the nucleus and scattering from correlated nucleon pairs are both likely to be important in this region.

In Fig. 4, inelastic electron spectra are compared with the pion data at similar momentum transfer [5]. The similarity between the spectra is remarkable. This is especially true if one notices that the pions that fill in the dip are resonance energy. Cascade model calculations [5], performed using a modified version of the code of Gibbs and Kauffmann [6], shown as solid curves in Fig. 5, predict a deep dip in this region due to absorption and scattering of these resonant pions on their way out of the nucleus.

The comparison between the data in the dip region and the cascade predictions points to the need for a mechanism that makes the nucleus transparent to pions at central nuclear densities with energies near the Δ resonance.

In Fig. 6, we compare QF data obtained on ^{208}Pb with that from deuterium. The data on deuterium can be taken as an isospin-averaged π-nucleon cross section. The deuterium data have been folded with a Gaussian to simulate the Fermi momentum expected in ^{208}Pb. The shapes of the spectra in the dip region are identical, again pointing to the need for some transparency at resonance energies. This has been verified by incorporating a hadronization time into the cascade model. When this time is set to 2 fm/c for the pions involved in pion production, the agreement between the calculations and the predictions is much better.



CLM_FIG4.MPR

Fig. 4. Comparison of the C(π, π') data at 50° and 70° to C(e,e′) data at nearly the same momentum transfer. The open circles are (π^+, π^+), the open squares are (π^-, π^-), and the solid black circles are (e,e′). The arrows indicate the energy loss of elastic scattering from ^{1}H. The (e,e′) data that are compared to the 50° (π, π') data are from Ref. [5]; and the (e,e′) data that are compared to the 70° (π, π') data are from Ref. [6] — see Ref. [5] for further details.

Possible sources of this transparency are: the possible need for a hadronization time for wave function of pions involved in pion production to settle into an eigenstate of mass; or a mechanism that allows the pions to be transported through the nucleus by a weakly interacting intermediate particle. One possible intermediate particle is the σ meson, which cannot interact through the Δ because it is isospin zero and so should have a longer mean-free path than the pion. If the σ width was around 50 MeV, it could be produced in the nucleus and would be likely to leave the nucleus without interacting before decaying into two pions. Other possibilities such as renormalized masses at central nuclear densities exist.

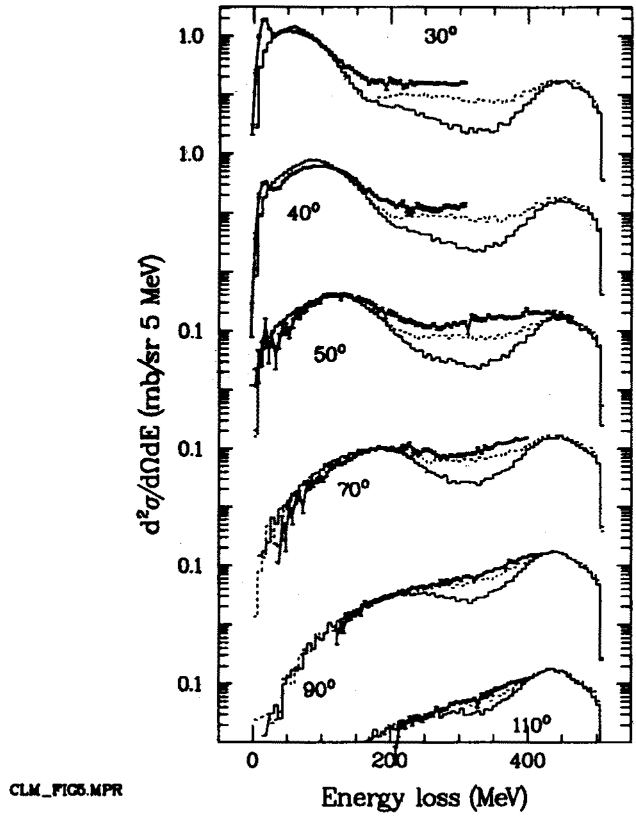


Fig. 5. The inclusive (π^-, π^-) spectra shown in Fig. 3 are compared with a standard Intra-Nuclear Cascade (INC) calculation (solid histograms). The dashed histograms are from an INC calculation where pion from $(\pi, 2\pi)$ reactions do not interact with the nucleus for a time equal to 2 fm/c.

4. Δ's in nuclei

In the quark model, the Δ(1232) is the first excited state of the nucleon. It is obtained by applying the $\sigma \cdot \tau$ operator to the nucleon. Although calculations that use the Δ–N mass difference and the size of nuclear matrix elements as their inputs have suggested virtual Δ's should exist in the nuclear wavefunction at the few-percent level, they have remained undetected to date despite significant experimental effort.

A successful measurement of these wavefunction components would provide tests of the short-range behavior of the nuclear wavefunction because it is in hard collisions that one expects these virtual Δ's to be created. How-

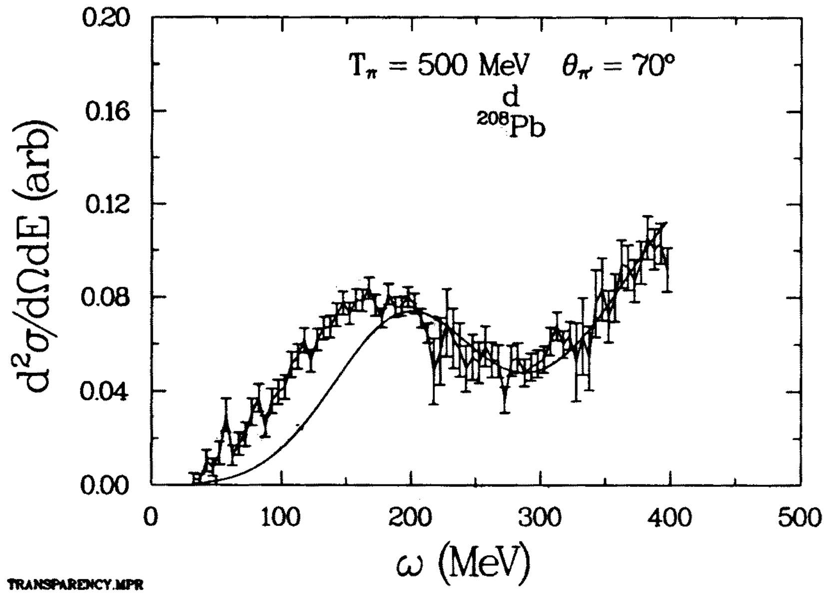


Fig. 6. Inclusive (π^+, π^+) spectra for ^{208}Pb (data points) and ^{2}H (solid line). the ^{2}H data have been folded with a Gaussian of width 110 MeV to simulate the effects of Fermi momentum.

ever, experimental signatures are difficult to find for at least two reasons. Firstly, since virtual Δ's are made in NN collisions, it is reasonable to expect the probability for finding Δ's to go up as the nuclear density squared. However, most strongly interacting probes scatter before reaching central nuclear densities. Secondly, since these wavefunction components are small one needs to find a mechanism that is not overwhelmed by first-order background. Both of these difficulties can be overcome by using the reaction $(\pi^+, \pi^- p)$ as a probe to search for Δ^-'s in nuclei.

The aforementioned long mean-free path at energies near 500 MeV implies that pions near this energy are able to probe the nuclear interior and thus may be sensitive virtual Δ's. We use the DCX reaction, $(\pi^+, \pi^- p)$, to search for Delta components of the nuclear wave function. Diagrams, which can contribute to the DCX reaction, are shown in Fig. 7. If only nucleonic degrees of freedom are considered there should not be features in the outgoing pion energy spectrum, such as the quasi-free peak, because of the larger energy losses and washed out kinematic signatures expected of a two-step reaction. This is the process shown in Fig. 7a. However, if one allows pionic and Delta degrees of freedom in the nucleus, other possibilities

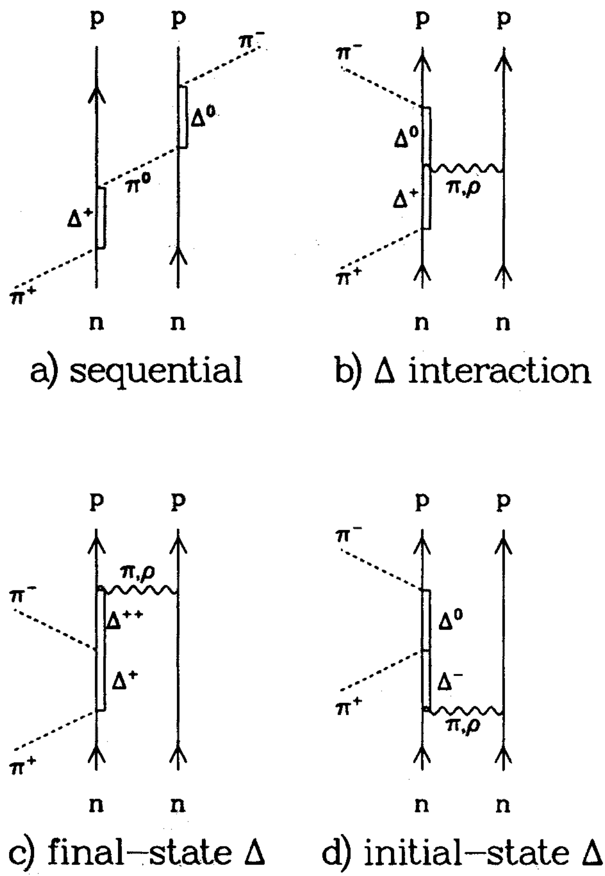


Fig. 7. Reaction mechanism diagrams for the (π^+, π^-) reaction.

emerge. Specifically, since the isospin of the Δ is 3/2, it exists in 4 charge states. The pion can transfer two units of charge to the Δ^- in a single step, as shown in Fig. 7d. This leads to the expectation of a significant enhancement in the cross section for DCX on Delta components of the nuclear wave function with respect to the two-step background.

The suggestion of using DCX as a probe of Δ's in the nuclear wave function is not new. Previously, DCX on Δ's was suggested as a mechanism that might explain the unexpected large cross sections for resonance-energy DCX between non-analog 0^+ states [7]. Subsequently, it was pointed out that in first order the spinless pion cannot cause the double spin flip necessary at 0° in the absence of distortions [8]. Although no calculations including distortions have been performed for this mechanism, calculations of Δ-charge-exchange scattering from the nucleus suggest this is a more likely process [8].

Protons coincident with the $(\pi^+, \pi^- p)$ DCX reaction at resonance energies were measured in an attempt to improve the signal to noise by using the kinematic signature of quasifree scattering. No enhancement was observed [9]. This work had no energy resolution for the coincident protons and consequently no missing-energy cut could be made. In addition, resonance-energy pions only reach the tenth density point and the virtual Delta probability is not likely to be large at these densities.

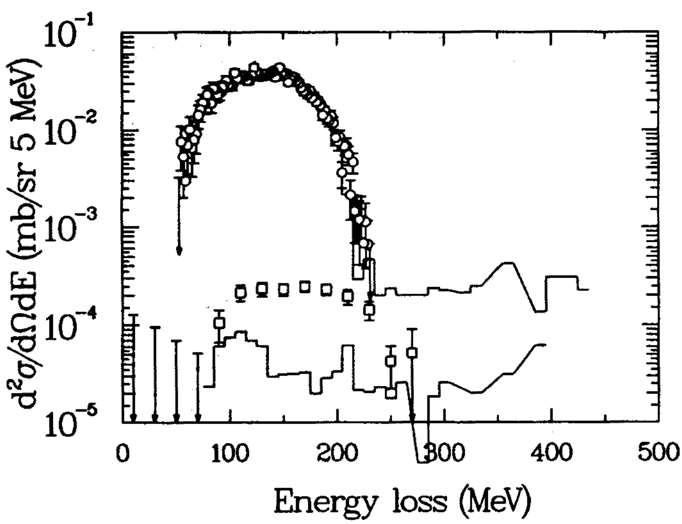


Fig. 8. Pion spectra for the exclusive reactions $^{12}C(\pi^+, \pi^+ p)$ (open circles) and $^{12}C(\pi^+, \pi^- p)$ (open squares) in the case of low missing energy ($E_{missing}$ <50 MeV). The beam energy is 500 MeV, the pions were detected at θ_{lab}=50° with the LAS spectrometer, and the protons were detected at θ_{lab}=−53° with a BGO phoswich detector. The histograms are estimates of these coincidence processes from an Inter-Nuclear Cascade code [6] calculation.

Proton coincidence data, taken in conjunction with the inelastic-scattering data described in the above section, are shown in Fig. 8. Here both non-charge exchange (NCX) $(\pi^+, \pi^+ p)$ and DCX $(\pi^+, \pi^- p)$ data are shown. The missing energy was required to be less than 50 MeV in the residual nuclei for both spectra. The protons were detected by a plastic BGO phoswich detector mounted at the QF recoil angle. This detector allowed measurement of proton energies up to 200 MeV. Above this energy the protons passed through the detector. The pion energy loss must be limited to less than 215 MeV in $(\pi^+, \pi^+ p)$ and 230 MeV in $(\pi^+, \pi^- p)$ to obtain reliable

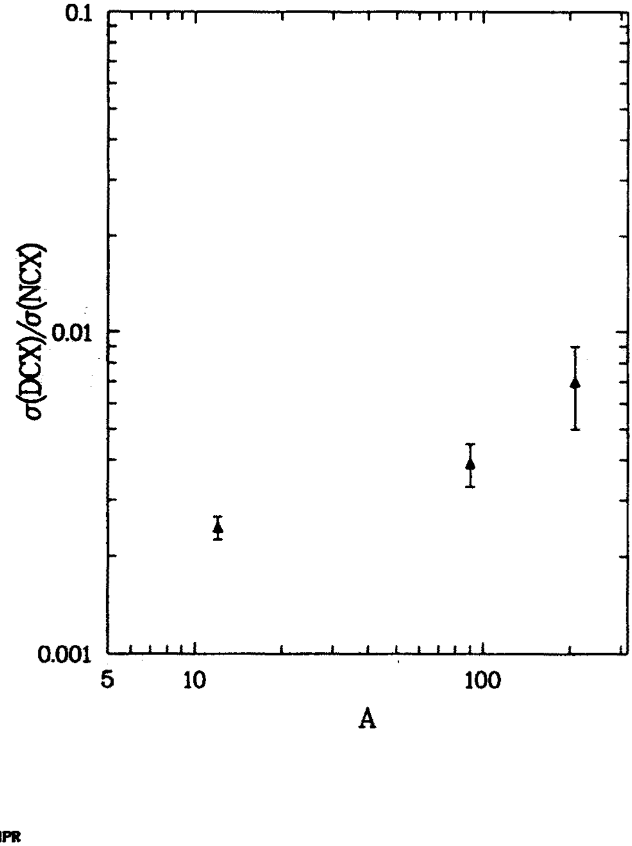


Fig. 9. The A dependence of the ratio of the pion peaks from $(\pi^+, \pi^- p)$ and $(\pi^+, \pi^+ p)$ in the case of low missing energy. The data shown are for targets of natural carbon, natural zirconium, and ^{208}Pb.

missing-energy cut. (The difference is due to the large negative Q-value for DCX.)

The presence of a peak near the QF energy in the DCX pion missing-energy spectrum is suggestive of the QF Δ-knockout mechanism proposed above. We have studied the reaction on the isotopic pairs ^{12,13}C and ^{40,44}Ca in an attempt to evaluate the importance of the more conventional two-step process, which couples a coherent SCX reaction with QF SCX. If this mechanism were important, one would expect to see a large difference in cross section (an order of magnitude) on these isotopic pairs because in ^{13}C and ^{44}Ca there is an analog state available for coherent SCX, whereas there is not in the other targets. No such enhancement was observed.

An estimate of the probability for pre-existing Δ's can be obtained from the data by integrating the cross sections in the peak and making the ratio (R) between DCX and NCX cross sections. This should cancel distortion factors and leaves:

$$R = P_{\Delta^-} \frac{\sigma(\pi^+ + \mathrm{p} \rightarrow \pi^+ + \mathrm{p})}{\sigma(\pi^+ + \Delta^- \rightarrow \pi^- + \mathrm{p})}, \qquad (2)$$

where P_{Δ^-} is virtual Δ^- probability. We have used quark-model coupling constants [10] to estimate the cross-section ratios assuming an intermediate Δ^-. This is not likely to be a good approximation but will probably give an overestimate of P_{Δ^-}. The resulting Δ^- probabilities are $\sim$10 times the ratio R that is shown as a function of A in Fig. 9. These are near the several-percent level.

5. Conclusions

Some recent data obtained for pion-nucleus interactions above the $\Delta(1232)$ at LAMPF have been presented. The expected long-mean free path at pion energies above the [3,3] resonance is observed as a much smaller strong absorption radius in carbon-elastic scattering observed at 500 MeV than at 180 MeV. Evidence for unexpected nuclear transparency at resonance energies is observed in large-energy-loss inelastic scattering. Finally, a new technique for measuring virtual Δ components of the nuclear wave function has been suggested and initial indications are that it give sensible results.

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