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TITLE: The Pion as a Probe of Nuclear Structure, What We Have and Have Not Learned

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The Pion as a Probe of Nuclear Structure,
What We Have and Have Not Learned

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I will discuss some experiments that have used the pion as a probe of nuclear structure. My talk will not be a comprehensive review. I have chosen examples of experiments that use the qualitative features of the π-nucleon interaction to study selectively certain aspects of nuclear structure. The talk is divided into five parts: (1) properties of the pion and the pion-nucleon interaction, (2) studies of the isospin mixing and neutron-to-proton matrix element ratios in inelastic scattering, (3) studies of isovector giant resonances in pion single-charge-exchange reactions, (4) the search for six-quark structures in the nucleus using pion double-charge-exchange reactions, and (5) concluding remarks.

A theme that runs through all work that seeks to use strongly interacting probes to observe the structure of the nucleus is the interplay of the incompletely known interaction mechanism and structure of the nuclear transition being studied. The cross sections that we measure involve both structure and interaction mechanism. The separation of these two aspects of the problem must begin with the qualitative features of the probe. Based on these qualitative features the experimenter can focus on those types of nuclear transitions that are best suited to study using a given probe. He may then design his experimental observation so as to minimize interaction-mechanism uncertainties.

Properties of the Pion and the Pion-Nucleon Interaction

The pion has isospin 1, hence it exists in three charge states, π^+, π^-, and π^0. These particles have a mass about 1/7, that of the nucleon mass. Pions having a kinetic energy comparable to their mass interact strongly with the nucleon forming a resonance (the (3,3) resonance) having isospin 3/2 and angular momentum 3/2. The pion-nucleon cross sections are shown as functions of momentum in Figure 1. The (3,3) resonance dominates the π-nucleon interaction at intermediate energies. At the peak of the (3,3) resonance the semiclassical estimate of the pion mean free path λ in nucleon matter is $\lambda = \frac{1}{\rho\sigma} = 0.7$ fm. Here ρ is the density of nucleons per cubic femtometer and σ is the isospin-averaged pion-nucleon total cross section. On the basis of this short mean free path it is to be expected that resonance energy pions will interact primarily in the nuclear surface. At energies above and below resonance energies the pion mean free path exceeds that of the nucleon and contributions to the scattering amplitude from the nuclear interior are to be expected.

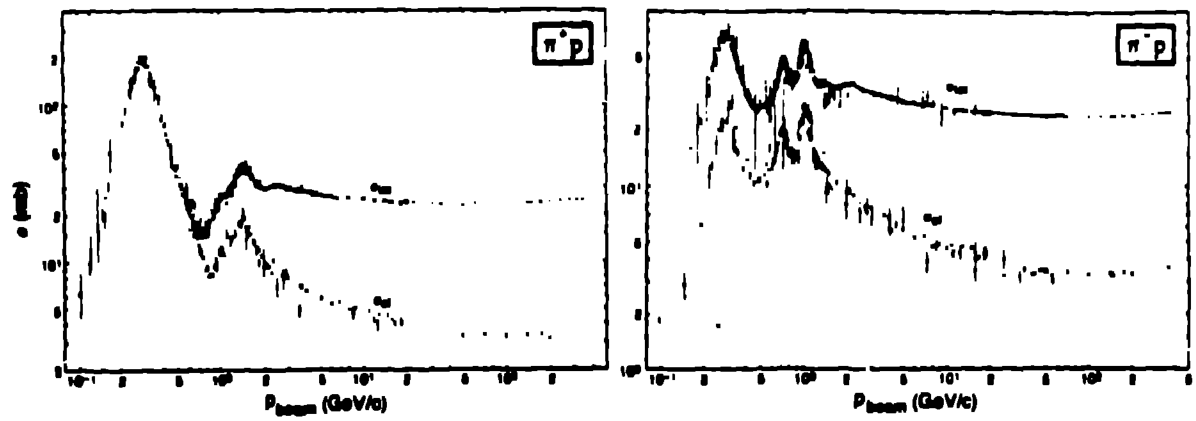

Figure 1. Pion nucleon total and elastic cross sections as functions of pion momentum.

Since the pion exists in three charge states a rich variety of reactions is possible. Both positive and negative pions may be used for elastic and inelastic scattering $((\pi^+,\pi^{+\prime})$ and $(\pi^-,\pi^{-\prime}))$. For nuclear targets both isospin-raising and -lowering charge-exchange reactions are possible $((\pi^-,\pi^0)$ and $(\pi^+,\pi^0))$. Two types of reactions are possible for pions that are not possible for the nucleon. The first is double charge exchange (π^+,π^-) and (π^-,π^+) and the second is pion absorpt. .n.

The pion-nucleon scattering amplitude may be written a ·

$$f = f_s + g_s \sigma \cdot \frac{k \times k'}{|k|^2}$$
$$f_v T \cdot \tau + g_v T \cdot \tau\sigma \cdot \frac{k \times k'}{|k|^2} \quad .$$

Here k and k' are the initial and final pion momenta, σ is the nucleon spin, T and τ are the pion and nucleon isospin and f_s, g_s, f_v, and g_v are coupling constants. At energies near the (3,3) resonance the coupling constants have the ratios

$$f_s \; : \; g_s \; : \; f_v \; : \; g_v \; = \; 4 \; : \; 2 \; : \; 2 \; : \; 1$$

and pion-nucleon cross sections have the ratios

$$\sigma(\pi^+ p \rightarrow \pi^+ p) \; : \; \sigma(\pi^- p \rightarrow \pi^0 n) \; : \; \sigma(\pi^- p \rightarrow \pi^- p) \; = \; 9 \; : \; 3 \; : \; 1 \quad .$$

Since the pion has spin 0 the nucleon spin couples to the pion orbital angular momentum. At forward scattering angles only non-spin-flip nuclear states are excited. At angles near 90° both spin-flip and non-spin-flip states are excited.

The experimental results that I will discuss were guided by the above considerations. In the inelastic scattering of positive pions the projectile couples nine times more strongly to the protons in the nucleus than to the neutrons. The opposite situation pertains for negative pions scattered by nucleons. In pion charge-exchange reactions only the $T \cdot \tau$ terms in the scattering amplitude are active, hence only isovector states are excited. In double-charge-exchange reactions at least two nucleons must be involved since only one unit of charge can be transferred in a pion nucleon collision. Therefore two-step processes play a leading role in double-charge-exchange reactions whereas two-step processes are higher order corrections in most other nuclear reactions.

The Study of Isospin Mixing and Neutron-to-Proton Matrix-Element Ratios in Pion Inelastic Scattering

In this section I will summarize work carried out by groups from the University of Minnesota, Los Alamos National Laboratory, the University of Texas, and the University of Pennsylvania. The studies were motivated by the 9:1 ratios of $\pi^+ p$ to $\pi^+ n$ and $\pi^- n$ to $\pi^- p$ scattering cross sections at (3,3) resonance energies. Both non-spin-flip and spin-flip transitions were studied.

In order to verify that the above 9:1 ratio pertains in the nucleus as well as for the nucleon, inelastic cross sections for both positive and negative pions were measured for well known $T = 0$ states in the $T = 0$ nuclei ^{12}C and ^{40}Ca.[1] Some of the results are shown in Figure 2. Since neutrons and protons contribute equally and symmetrically to the wave functions of $T = 0$ states in $T = 0$ nuclei one would predict that the differential cross sections for positive and negative pions would be the same. The experimental results verify this prediction.

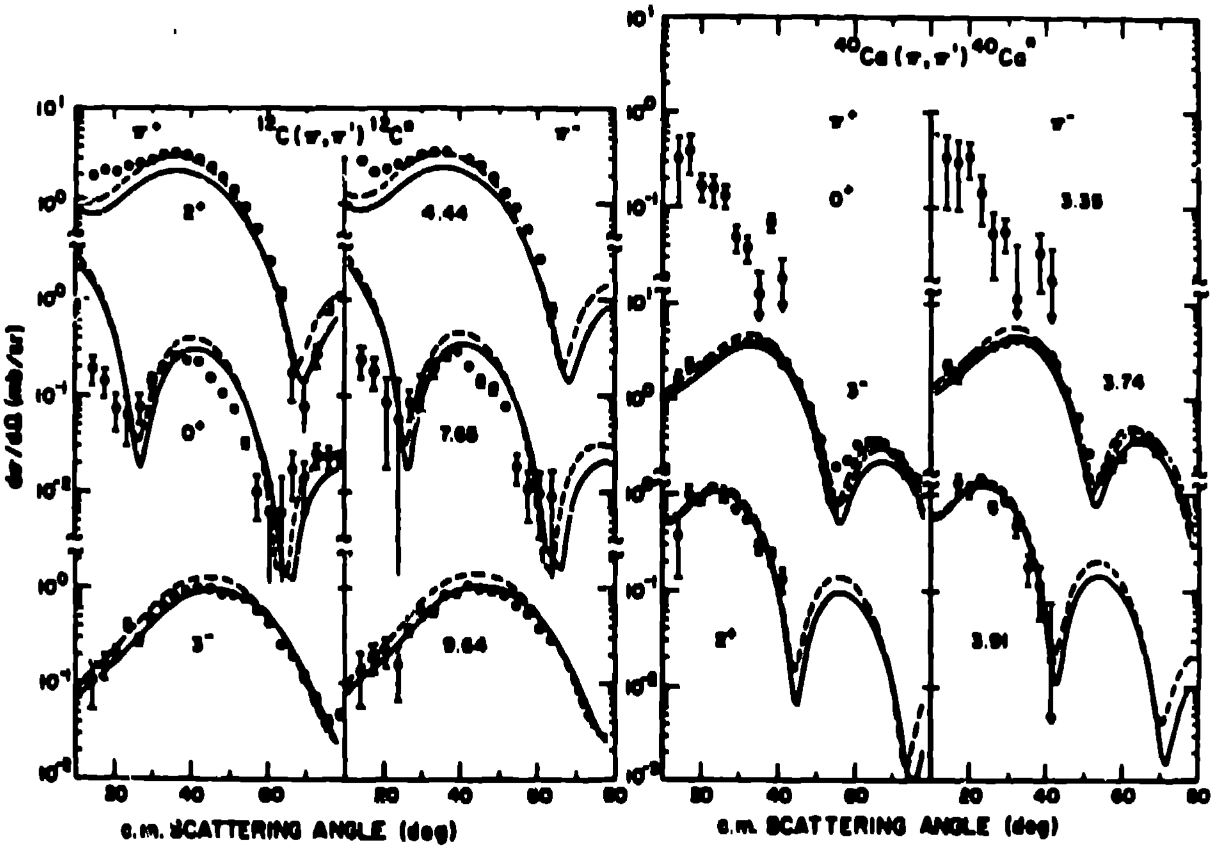

Figure 2. Comparison of π^+ and π^- differential cross sections for $T = 0$ states in ^{12}C and ^{40}Ca.

Two additional experiments give confidence that the ratio of 9:1 applies in the nuclear medium. The $9/2^+$ at 9.5 MeV in ^{13}C is formed by promoting a $1p3/2$ neutron to the $1d5/2$ shell. Detailed shell-model calculations[2] indicate that this state is a pure neutron excitation. Therefore the ratio of π^+ to π^- cross section is expected to be 1:9. Figure 3 shows the experimental results. The ratio is indeed 1:9.

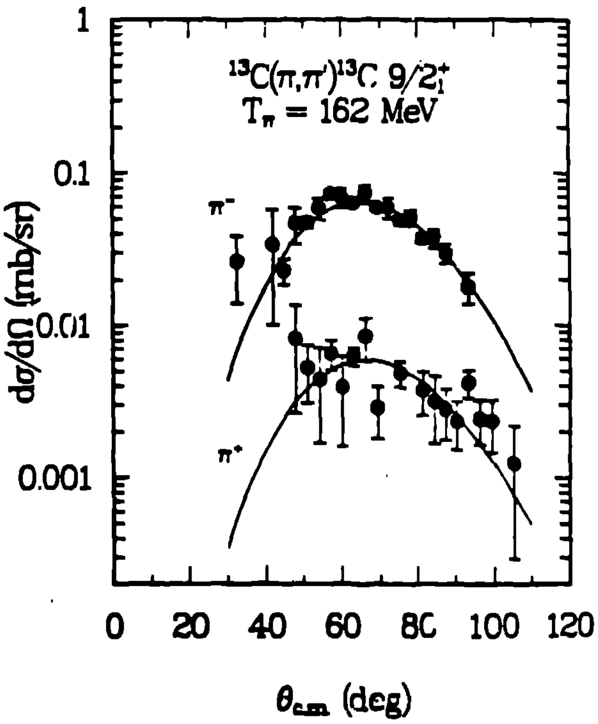

Figure 3. Comparison of π^- and π^+ inelastic differential cross sections to the $9/2^+$ state in ^{13}C at 9.5 MeV.

A quantitative test of the ability of $\pi^+ : \pi^-$ matrix elements to yield isospin mixing ratios has been provided by the $J^\pi = 1^+$ states in ^{12}C at 12.71 and 15.11 MeV. The lower state is primarily $T = 0$ and the upper state is $T = 1$. These states are known to be isospin mixed and the amount of mixing has been measured by Flanz et al.[3] using 180° electron scattering. The ratio of 180° electron cross sections for these two states in the absence of isospin mixing would be the ratio of isoscalar to isovector magnetic moments squared,

$$\frac{\sigma_0}{\sigma_1} = \left|\frac{\mu_n + \mu_p}{\mu_n - \mu_p}\right|^2 = \frac{1}{28} \quad .$$

From the measured ratio Flanz et al. deduce a mixing matrix element of $H_{10} = 140 \pm 35$ keV. The π^+ to π^- cross-section ratio for these two states has been measured by Morris et al.[4] From the deviation of the ratios from unity Morris et al. deduce a mixing matrix element of $H_{10} = 148 \pm 26$ keV in agreement with the value from 180° electron scattering.

As indicated above the pion inelastic scattering near 90° is a good probe of isoscalar spin-flip strength. A class of states in p-shell nuclei having $\Delta J^\pi = 4^-$, $\Delta L = 3$, $\Delta S = 1$ has been discovered in pion inelastic scattering. These states are formed by transitions of the type $[1d3/2^-, 1d5/2]_{4^-}$. An example is the 4^- doublet in ^{12}C at 19.25 and 19.65 MeV. The π^+ to π^- cross-section ratios for these states are shown in Figure 4. Remarkably the π^+ to π^- ratio for the 19.25 MeV state is close to 9:1. The π^+ to π^- ratio for the 19.65 MeV state is close to 1:9. Therefore these states are nearly pure proton and neutron excitations due to strong isospin mixing.

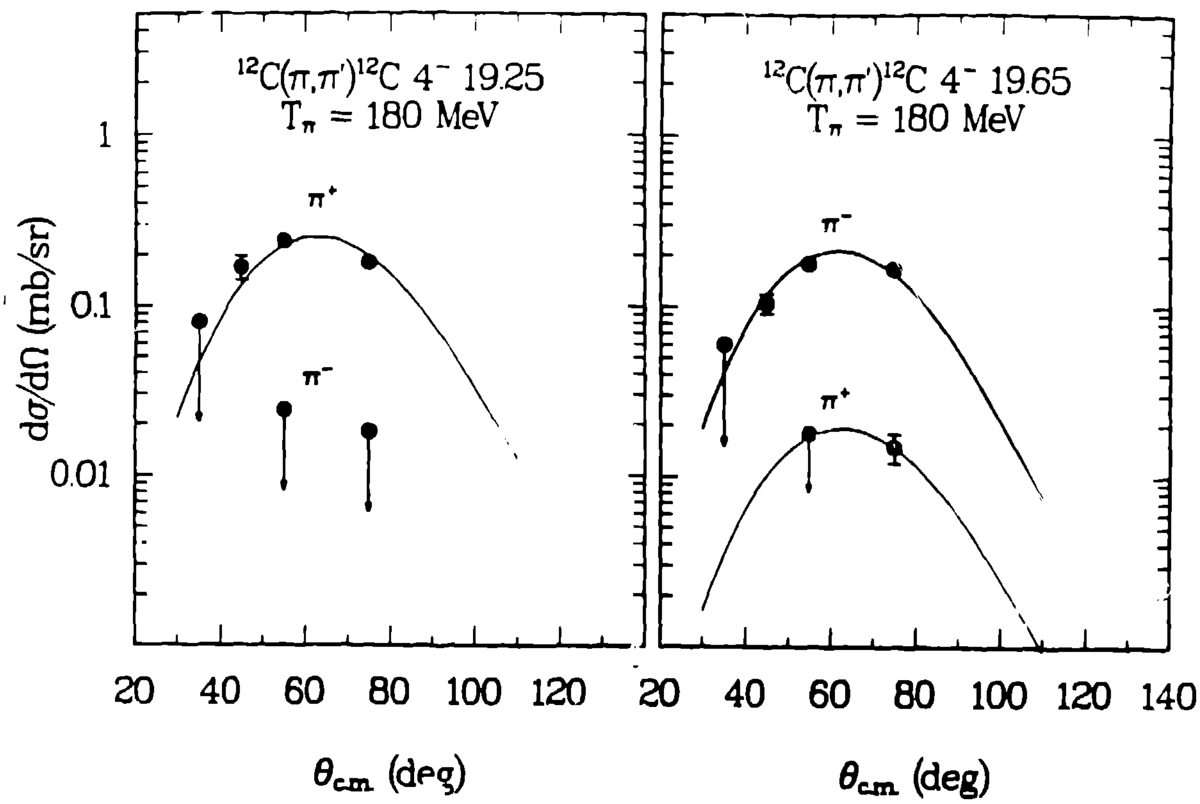

Figure 4. Comparison of π^+ and π^- cross differential cross sections for the isospin mixed doublet in ^{12}C.

Efforts to study the isospin structure of isoscalar quadrupole giant resonance in heavy nuclei have yielded interesting results.[5,6] The interpretation of $\pi^+ : \pi^-$ cross-section ratios for nuclei with a large neutron excess will be difficult for two reasons. First, the isovector distortion of the incident pion waves is not well known. For nuclei with a large neutron excess the π^- waves will be absorbed more than the π^+ waves and increase the $\pi^+ : \pi^-$ cross-section ratios. Second, the Coulomb force will cause the proton part of the transition density to extend to larger radii than the neutron part of the transition density. This effect will also increase the π^+ to π^- cross-section ratio since the resonance-energy pions interact primarily in the surface. The observed $\pi^- : \pi^+$ cross-section ratio for the collective 3^- first excited state of ^{208}Pb in which neutrons and protons participate in the ratio $N : Z$ has been measured to be 1.8 ± 0.1.[6] The measured $\pi^- : \pi^+$ ratio for the isoscalar quadrupole giant resonance peak in ^{208}Pb has a much larger value of 2.7 ± 0.5.[6] This result would indicate a substantial amount of isovector admixture in the isoscalar quadrupole resonance, but one must bear in mind the above reservations. A better characterized isovector optical potential is necessary for the quantitative interpretation of π^- to π^+ cross-section ratios in nuclei having a large neutron excess.

In summary the measurement of $\pi^+ : \pi^-$ cross sections in inelastic scattering has been used to study isospin mixing in $T = 0$ nuclei and to measure neutron-to-proton matrix-element ratios. A class of isospin-mixed $J^\pi = 4^-$ states in p-shell nuclei has been discovered and studied. The extension of this technique to nuclei having large neutron excess has yielded intriguing results but the quantitative interpretation of measured ratios is made ambiguous by interaction-mechanism uncertainties.

The Study of Isovector Resonances in Pion Single-Charge-Exchange Reactions

In this section I will discuss the results of a series of experiments carried out by a collaboration of Tel-Aviv University and Los Alamos National Laboratory, which studied the excitation of $L = 0$, 1, and 2 isovector giant resonances in pion charge-exchange reactions $(\pi^{\pm}, \pi^0)$.[7]

Giant resonances are excitations of the nucleus in which large numbers of nucleons move collectively. They are simple modes of nuclear excitation that can be interpreted microscopically or macroscopically. Their experimental observation and study as well as their theoretical interpretation are important for models of nuclear excitation and the knowledge of the nucleon-nucleon interaction in the nuclear environment. The experimental properties that characterize a giant resonance are the concentration of a large fraction of the total available transition strength with specific quantum numbers in a narrow region of excitation energy, the occurrence of resonances in a wide range of nuclei, and the smooth variation of excitation energy and width of the resonance with nuclear mass A. In contrast to the isoscalar electric modes, which have been extensively studied in the scattering of hadronic probes, the $L = 1$, $T = 1$ or giant dipole resonance (GDR), which has been studied with electromagnetic probes, and the $L = 0$, $T = 1$, $S = 1$ Gamow-Teller resonance, which has been studied in the (p, n) reaction, the $L = 0$ $T = 1$ isovector monopole resonance (IVM) and $L = 2$, $T = 1$ isovector quadrupole resonance (IVQ) were poorly characterized before pion charge-exchange studies. The study of the IVM was of particular importance. Its existence had been predicted by both macroscopic[8] and microscopic[9] theories, but it had not been observed. The IVM plays a central role in Coulomb effects such as isospin mixing in nuclear ground states, Coulomb displacement energies and widths of analog states.

The quantum numbers and dynamical properties of resonance-energy pions make the pion charge-exchange reactions $(\pi^{\pm}, \pi^0)$ ideal for the study of electric isovector resonance especially the IVM. First, the use of a charge-exchange reaction that excites only isovector states eliminates the excitation of isoscalar states that dominate the excitation spectra of inelastic scattering processes. Second, at forward angles, where the angular distribution of the IVM peaks, pion charge exchange excites primarily electric, or non-spin-flip transitions (in contrast to the (p, n) reaction), reducing spin-flip backgrounds. Third, the strong absorption of the pion is essential for the excitation of a monopole state for which the volume integral of the transition density is zero. The angular distributions produced by the surface-related diffractive pion scattering process [similar to $((\alpha, \alpha'))$] oscillate sharply and characteristically with angle.[10]

$$\frac{d\sigma}{d\Omega} \sim J_0^2(kR\theta) \quad \text{for} \quad L = 0$$
$$\frac{d\sigma}{d\Omega} \sim J_1^2(kR\theta) \quad \text{for} \quad L = 1$$
$$\frac{d\sigma}{d\Omega} \sim J_0^2(kR\theta) + 3J_2^2(kR\theta) \quad \text{for} \quad L = 2 \quad ,$$

where k is the π momentum, θ is the scattering angle and R is the strong absorption radius. This rapidly oscillating behavior serves to identify the multipolarity of the transition and to distinguish the giant resonance signals from the nonresonant background. In Figure 5 representative angular distributions for the ^{60}Ni (π^-, π^0) reaction at 230 MeV are shown. The qualitative patterns of the angular distributions do not depend on the details of the reaction model used so long as the pion waves are strongly absorbed.

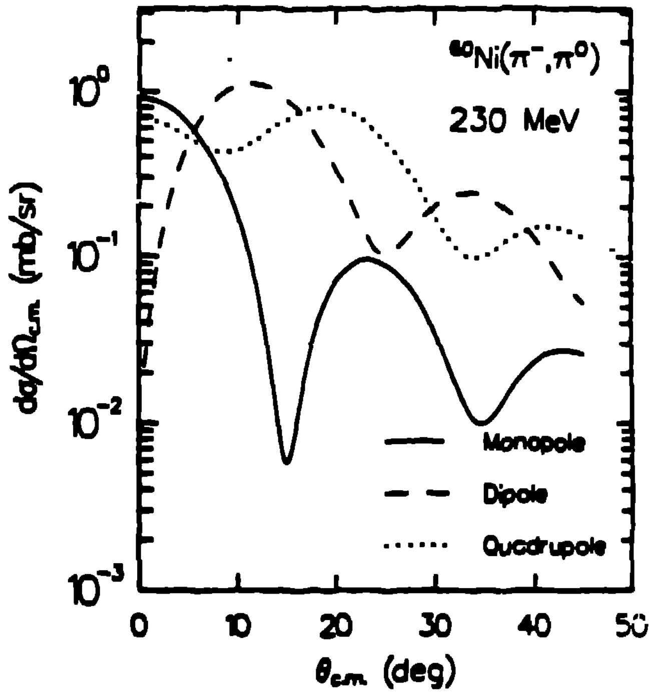

Figure 5. Angular distribution for L = 0, 1, and 2 collective transitions for 230 MeV (π^-, π^0) reactions on ^{60}Ni.

Fourth, the Coulomb energy shift for states populated by the (π^-, π^0) reaction is advantageous. This point is illustrated in Figure 6 where the analog state relations are shown for an isovector resonance built on a target ground state of isospin T. For nuclei with $T \gg 1$, transitions to the state of lowest total isospin are strongly favored by isospin coupling coefficients. The state of total isospin $T+1$ in the (π^-, π^0) daughter is shifted down by the Coulomb displacement energy relative to its analog in the parent nucleus. Thus the $T+1$ state has a relatively low excitation energy in the (π^-, π^0) daughter and occurs at an excitation energy where the density of states of the same isospin is small. The opposite situation pertains for the (π^+, π^0) reaction. The $T+1$ component populated in the (π^-, π^0) reaction is expected to be narrow and to occur at a low excitation energy while the $T-1$ component populated in the (π^+, π^0) reaction is expected to be wide and to occur at a high excitation energy.

In the experiments well-understood, spherical, even-even nuclei were studied in the $(\pi^\mp, \pi^0)$ reactions at 120, 165, and 230 MeV. Double differential cross sections up to excitation energies of 60 MeV were measured out to angles extending well past the second maximum of the IVQ angular distribution. Data for the ^{120}Sn target with a 165 MeV π^- beam are shown in Figures 7a and 7b. At the most forward angle, 4.5°, the IVM cross section is expected to be the largest. The second angle, 11°, is chosen to be near the first minimum of the monopole angular distribution. The GDR cross section is small at the forward angle and has a maximum near 11°. Figure 7c shows the results of subtracting the 11° spectrum from the 4.5° spectrum. This subtraction suppresses the approximately isotropic non-resonant background. The IVM signal is the positive-going hump and the small GDR signal is the negative-going hump.

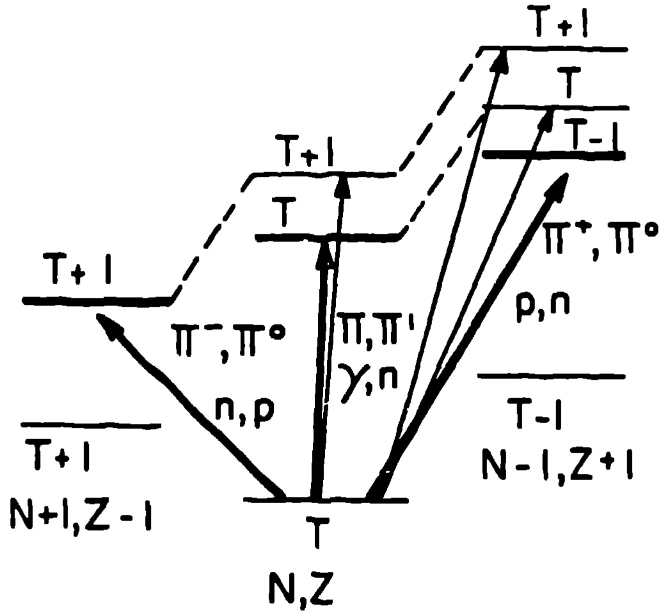

Figure 6. Analog relationships for isovector resonances built on a $T \geq 1$ target nucleus.

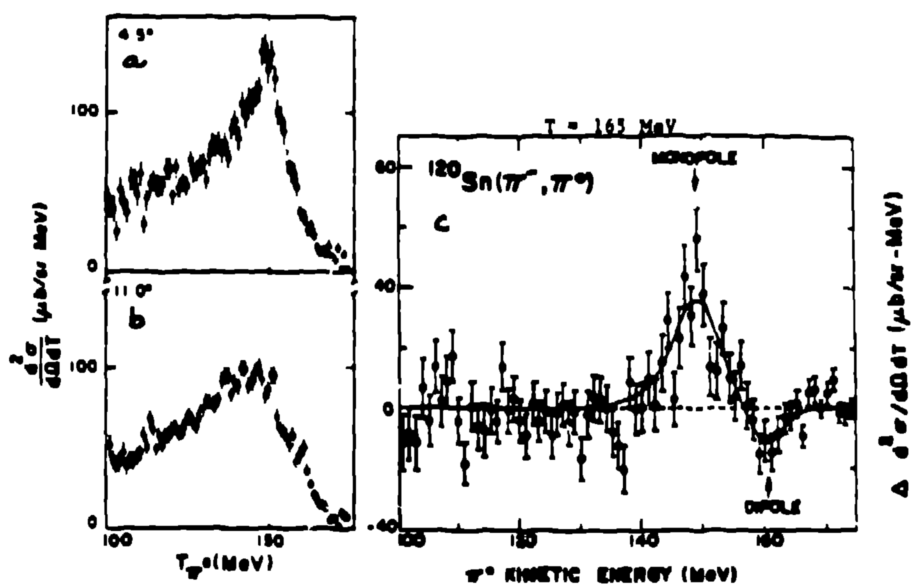

Figure 7. Figures 7a and b show the double differential cross section as functions of T_{π^0} In the $^{120}\mathrm{Sn}(\pi^-,\pi^0)$ reaction at a forward angle where the IVM cross section is large (a) and at a larger angle where the IVM cross section is small (b). Figure 7c shows the difference of the 4.5° and 11° spectra.

The above analysis shows the existence of peaks above an approximately isotropic background in the $d^2\sigma/d\Omega dE$ versus pion kinetic energy spectra. The IVM peak is visible in a comparison of the 4.5° and 11° spectra but the GDR peak is not. The subtraction procedure makes the weak GDR peak visible. To investigate the degree of isotropy of the non-resonant background it is necessary to look at the dependence of different regions of excitation energy on scattering angle or momentum transfer

q. Figure 8 shows the forward-angle data for ^{60}Ni (π^-, π^0) taken at 230 MeV. As before, the IVM is large in the most forward angle where the GDR is small. The IVM is small at the second angle where the GDR is large and both are small at the largest angle. In general cross sections depend on energy loss ν and momentum transfer q^2. Figure 9 shows $d\sigma/d\Omega$ obtained by integrating over the three regions indicated in Figure 8. Region one emphasizes the IVM, region two emphasizes the GDR and region three contains mostly nonresonant background. Each plot can be represented as a superposition of a background linear in q^2 and a component having the q^2 dependence expected for $d\sigma/d\Omega$ for a $L = 0$ or 1 resonance. Although the background is not strictly isotropic its dependence on q^2 is much less rapid than that of the giant resonances.

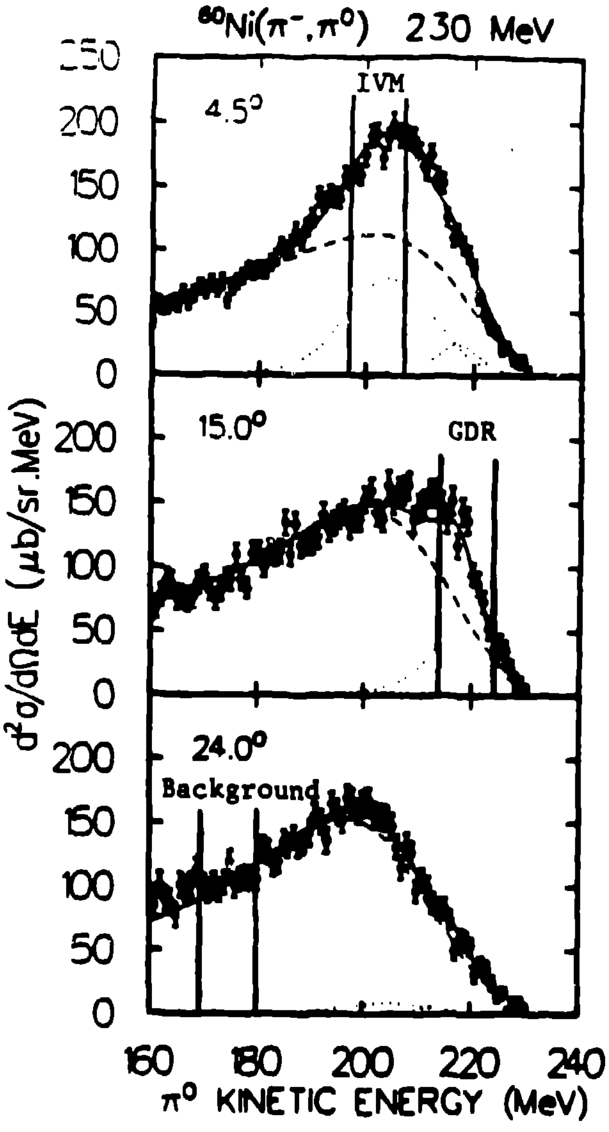

Figure 8. Doubly differential cross sections as functions of T_{π^0} for scattering angles of 4.5°, 15.0°, and 24.0° for the ^{60}Ni(π^-, π^0) reaction at 230 MeV.

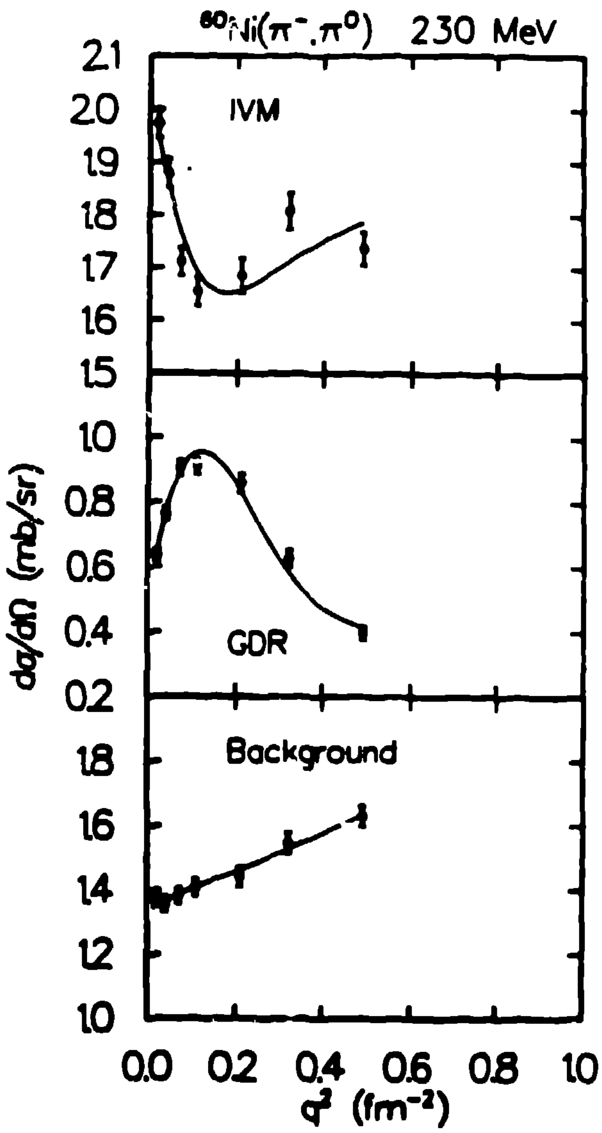

Figure 9. Singly differential cross sections obtained by integrating over the T_{π^0} regions shown in Figure 8, as functions of momentum transfer squared. The solid lines are fits to a linear background added to a $L = 0$ or $L = 1$ angular distribution for the IVM and GDR respectively.

In order to extract quantitatively excitation energies, widths, and maximum cross section, a least-squares fitting procedure was followed. The double differential cross section as a function of q^2 and ν was written as a sum of two Gaussian peaks at an angle-independent excitation energy. The q^2 variation of the peaks was taken to be that of distorted wave impulse approximation calculations using random phase approximation (RPA)[11] transition densities. The sizes of the maximum cross sections were varied. The background was written as a function having a smooth ν-dependence and a quadratic q^2-dependence. Resonance and background parameters were varied to fit the data for each target. For targets where data were taken at different bombarding energies, the extracted resonance energies and widths were consistent although the background shapes were different. The background function and the resonance components shown in Figure 8 were obtained in this way.

Figure 10 shows the extracted maximum cross sections, excitation energies, and widths for the IVM and GDR resonances with results of random-phase-approximation distorted-wave-impulse-approximation (RPA-DWIA) calculations.[11] The A dependence of the 1 $\hbar\omega$ GDR cross sections can be understood as follows. In the (π^-, π^0) reaction a proton is turned into a neutron and is promoted by one major shell. For

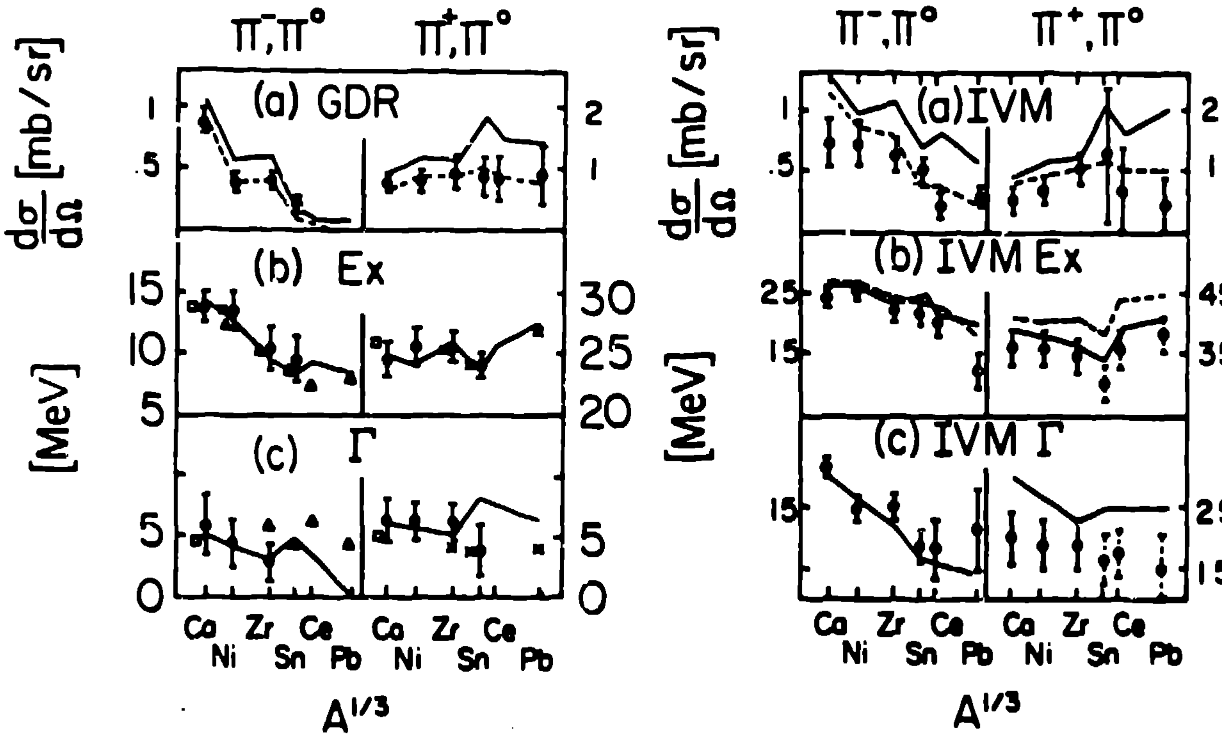

Figure 10. Extracted maximum cross sections, excitation energies, and widths for the GDR and IVM resonances. The lines are the results of random phase approximation[11] calculations done before the data were available.

the $T = 0$ nucleus, ^{40}Ca, there is no blocking and the π^+ and π^- cross sections are comparable. For ^{208}Pb the neutron shell is fully occupied and the (π^-, π^0) cross section for the GDR is zero. The same effect is seen to a lesser extent for the A dependence of the 2 $\hbar\omega$ IVM maximum cross sections. Here the (π^-, π^0) IVM cross sections decrease by about a factor of two from ^{40}Ca to ^{208}Pb while the (π^+, π^0) IVM cross sections are approximately constant. As expected, the widths and excitation energies of $T+1$ states are larger than those of the corresponding $T-1$ states. Where data are available from other reactions, they are also shown. The solid curves give the theoretical results for multiple strength weighting and the dashed curves give the results for cross section weighting. The cross-section-weighted RPA theory using the Skyrme III residual interaction(11) gives a reasonable description of the data.

Remarkably, no IVQ peak was necessary to fit the experimental double differential cross section data. In order to quantify the amount of IVQ cross section present in the data, a third Gaussian peak was added to the fitting function. The excitation energy, width, and q^2-dependence of the peak were taken from RPA-DWIA calculations. The data were refitted and 90% confidence level upper limits were deduced for the presence of an IVQ component. These upper limits were 0.18, 0.30, and 0.15 of the RPA-DWIA estimate of the peak IVQ cross section for ^{40}Ca, ^{60}Ni, ^{90}Zr (π^-, π^0) respectively. For the IVM and GDR the observed cross sections were typically 0.7 of the RPA-DWIA calculations. If a much larger width was assumed the upper limit for the IVQ cross section was increased and became consistent with the RPA-DWIA estimate.

An interesting explanation of the absence of isovector quadrupole strength in the pion charge-exchange reaction has been proposed by Leonardi et al.(12) They argue in a sum rule framework that the inclusion of non-local terms in the residual interaction would have little effect on the properties of $L = 0$, 1, and 2 isovector giant resonances in $\Delta T_z = 0$ channels, and on the properties of the $L = 0$ and $L = 1$ isovector resonances in charge-exchange channels. Thus RPA calculations with local interaction could correctly describe these properties of these isovector giant resonances even if the true residual interaction were non-local. However, Leonardi et al. argue that the inclusion of non-local residual interaction could radically broaden and weaken the isovector quadrupole resonance in the charge-exchange channels. The absence of isovector quadrupole strength in the pion charge-exchange reactions has been a problem and Leonardi's explanation is intriguing.

To summarize this section, the isovector monopole resonance has been observed in the pion charge-exchange reaction. The properties of the charge-exchange components of the isovector monopole and dipole resonances have been studied and found to be in good agreement with RPA predictions. No charge-exchange isovector quadrupole strength was observed. An explanation in terms of non-local residual interaction has been suggested.

Search for Six-Quark States in Nuclei Using Double Charge Exchange

The search for six-quark clusters in pion double charge exchange was motivated by the weakness of the pion-nucleon interaction at 50 MeV, which allows the pion to probe the nuclear interior at this energy, and by the existence of a cancellation between the s and p wave amplitudes for pion-nucleon single charge exchange at zero degrees. Both the s and p wave amplitudes are nearly real at low energies. The s-wave amplitude increases as k while the p-wave amplitude increases as k^3. Their signs are opposite and a cancellation occurs at 50 MeV. This cancellation also dominates the energy dependence of the π-nucleus charge charge-exchange reaction leading to the isobaric analog state. Figure 11 compares the bombarding energy dependence of nucleon charge exchange cross sections at zero degrees and the reaction leading to the isobaric analog state $^{14}C(\pi^+,\pi^0)^{14}O$ (IAS) at zero degrees.[13] This interference minimum has been studied for nuclei from ^{7}Li to ^{120}Sn.[14] Remarkably the minimum persists even in heavy nuclei. Due to the *s*-*p* interference at 50 MeV, the angular distribution for pion charge exchange on the nucleon is backward peaked. Angular distributions of single charge exchange reactions leading to the IAS have been measured for the nuclei ^{7}Li, ^{14}C, and ^{15}N[15] at 50 MeV. These angular distributions were also found to be backward peaked, reflecting the behavior of the elementary process. If the isobaric analog state were the dominant intermediate state for double charge exchange leading to the double-isobaric-analog state one would expect backward peaked angular distribution for this process as well.

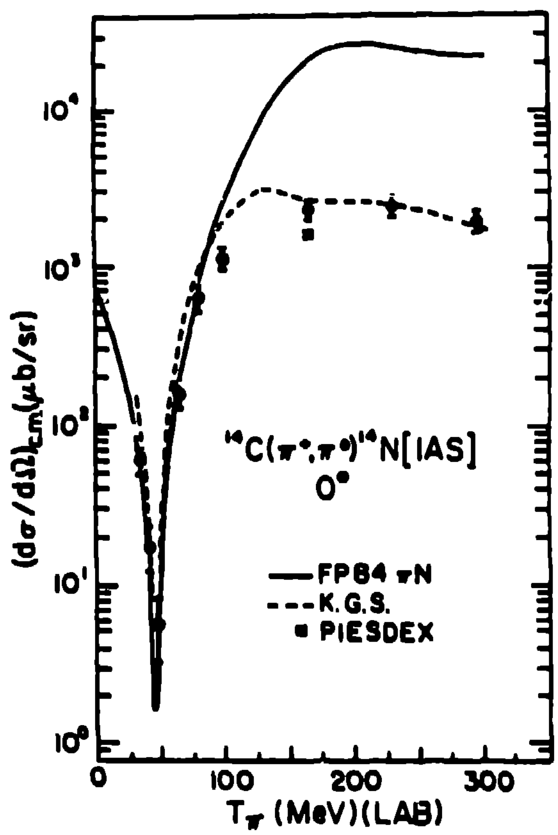

Figure 11. Zero-degree cross section for the reaction $\pi^- p \rightarrow \pi^0 n$ (solid line) compared to the zero-degree cross section for the reaction $^{14}C(\pi^-,\pi^0)^{14}N$ (IAS)[13] as functions of the π^- kinetic energy.

Measurements of the double-isobaric-analog state transition by Navon et al.[16] on ^{14}C, $^{14}C(\pi^+,\pi^-)^{14}O$ showed an unexpectedly large cross section. Furthermore the differential cross section was increasing as the scattering angle decreased. The most forward angle of this measurement was 50°. Distorted wave impulse approximation[16,17] calculations based on the idea that the isobaric analog state was the dominant intermediate state predicted a zero-degree cross section of about 0.2 μb/sr at zero degrees, which increased to a few hundred μb/sr at backward angles.

Miller[18] proposed a new interaction mechanism that could lead to large forward-peaked double-isobaric-analog state cross sections while keeping the single-charge-exchange isobaric-analog-state cross section small. He argued that when the two valence neutrons in ^{14}C were closer than about 1 fm (about 6% of the time) they would exist in a six-quark state. In his calculations for the structure of this state a π^+ could flip the isospin of two down quarks to up and emerge in the forward direction as a π^-. The zero-degree cross section was calculated to be 11 μb/sr. An experiment was carried out at Los Alamos that measured the zero-degree cross section to be 4 μb/sr. The results of this experiment as well as various theoretical calculations are shown in Figure 12. Clearly Miller's approach better explained the experimental results than did the sequential isobaric-analog-state hypothesis. The inclusion of a realistic amount of absorption brought Miller's original calculation of the zero-degree cross section down to 4 μb/sr in agreement with the experiment.

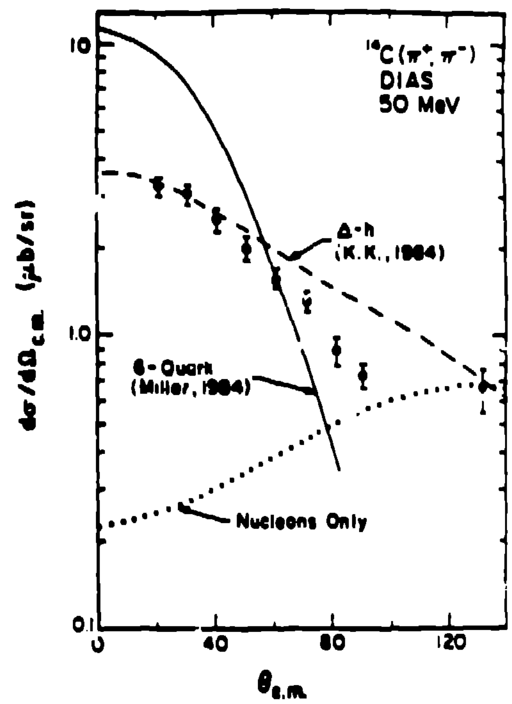

Figure 12. Measured $^{14}C(\pi^+,\pi^-)^{14}O$ DIAS cross sections compared with three theoretical calculations, see text.

Karapiperis and Kahagashi[19] proposed an explanation for the large zero-degree double-isobaric-analog-state cross section, which does not require non-nucleonic degrees of freedom. These authors calculated the double-isobaric-analog-state cross section in a delta-hole approach. They included non-analog intermediate states in the closure approximation. Their calculation is shown in Figure 12 and compares well to the experimental data. Gibbs[20] also obtained large forward-peaked cross sections by including non-analog intermediate states Both groups point out the importance of sequential single-charge-exchange scattering processes at large angles. Although the zero-degree single-charge-exchange cross section is small, the ninety-degree cross section is not. Two sequential scatterings at ninety degrees can lead to double charge exchange at zero degrees. An interesting feature that emerges from the work of Gibbs[20] is the important role of short-range nucleon-nucleon correlations. About half the scattering amplitude comes from double scatterings where the two struck nucleons are separated by less than 1 fm.

To summarize this section one must say that double-charge-exchange studies have not led to an unambiguous identification of six-quark structures in the nucleus. Attempts to understand the large forward-peaked double-isobaric-analog-state cross sections have brought to our attention the need for a better understanding of the role of non-analog intermediate states in the double-charge-exchange reaction. The expectation that double charge exchange is a good probe of nucleon pairs at short distances retains its validity. However, in order to use the double-charge-exchange reaction as a quantitative probe of short-range correlations, a better understanding of the pion nucleus reaction mechanism than we have at present is required.

Conclusion

The isospin structure of the pion makes it a specific probe of interesting aspects of the structure of nuclei. Successful investigations of separate neutron and proton components in nuclear transitions have been carried out in pion inelastic scattering. The isovector-monopole giant resonance has been discovered in pion charge-exchange scattering and the isospin structure of the isovector-monopole and isovector-dipole giant resonances have been studied. In these investigations as well as in studies of short-range nucleon-nucleon correlations in double charge exchange, reaction-mechanism uncertainties have been a serious problem in the quantitative interpretation of data, although experiments have been designed to exploit qualitative features of the pion-nucleon-scattering process, which minimize reaction-mechanism uncertainties.

In my opinion the field of pion-nucleus physics would benefit from experiments aimed at constraining reaction-mechanism uncertainties. Excellent elastic and inelastic pion-nucleus cross-section data over a wide range of scattering angles and bombarding energies are available. Double-charge-exchange experiments are more difficult, but a body of data exists for analog and non-analog transitions for a range of nuclei, energies above, near, and below the (3,3) resonance. For pion charge exchange the experimental data are much less complete. Only forward-angle cross sections leading to the isobaric analog state have been measured due to the limitations of existing instrumentation. Measurements of isobaric-analog-state cross sections to large angles are needed. Double-charge-exchange studies have indicated the importance of non-analog intermediate states. To study these effects it is important to study inelastic, single charge exchange and double charge exchange to final inelastic nuclear states, which are themselves related by isospin symmetry. I believe that the availability of such data would not only lead to a better phenomenological characterization of the isospin dependence of the pion-nucleus optical potential, but also to an understanding of the interesting underlying pion dynamics in the nuclear medium.

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