LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

LA-UR -90-2737

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--90-2737

DE90 016510

TITLE: # MULTI-NUCLEON PHENOMENA IN PION-NUCLEUS REACTIONS

AUTHOR(S): *Peter A. M. Gram*

DISCLAIMER

SUBMITTED TO: The Proceedings of the 12th International Conference on Particles and Nuclei (PANIC XII), Cambridge, MA, June 24-30, 1990

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO. 836 R4
ST. NO. 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

MULTI-NUCLEON PHENOMENA IN PION-NUCLEUS REACTIONS

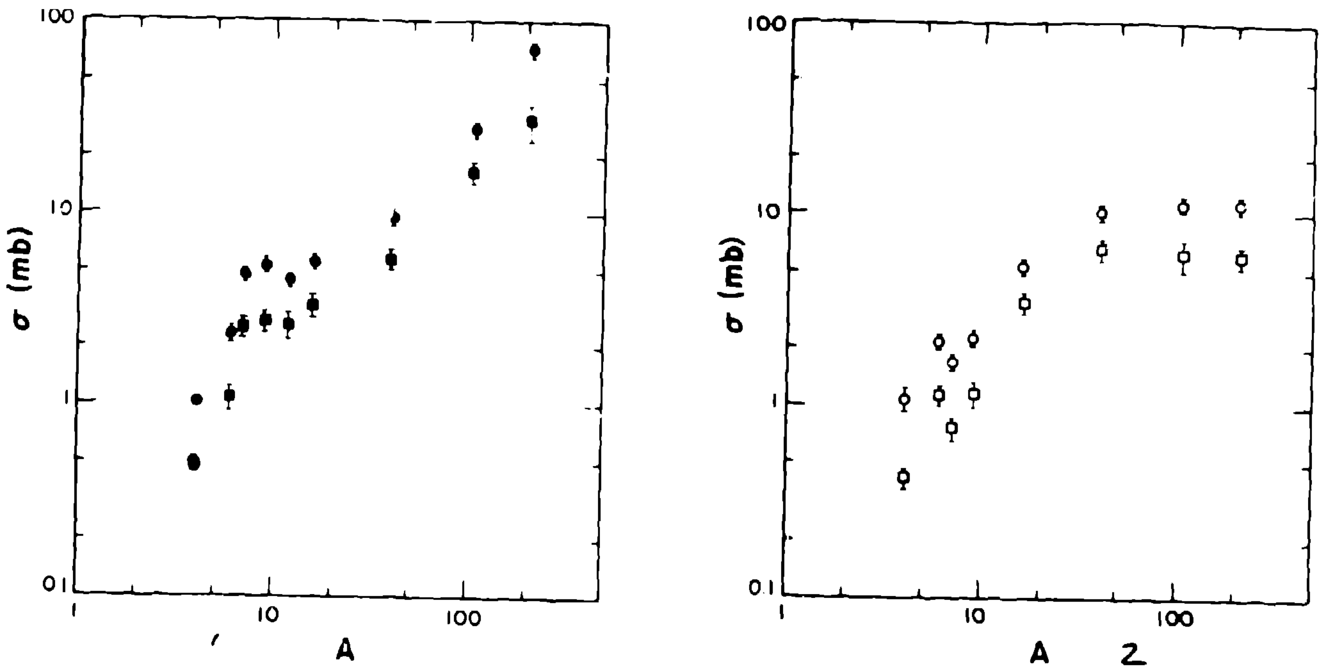
Peter A. M. Gram

Los Alamos National Laboratory, Los Alamos, NM 87545

At the peak of the delta resonance, the pion is the most strongly interacting particle we know. It follows that interactions between pions and nuclei at these energies all tend to involve multiple scattering to some degree. Multiple scattering includes different kinds of processes. In its simplest forms, it involves a sequence of interactions with single nucleons that take place as the pion bumbles its way through a nucleus. Much more interesting is the possibility that there are interactions that in some sense directly involve several nucleons at once. If there are such interactions, can we distinguish between them and the simpler, more prosaic forms of multiple scattering? Experimental study of pion-nucleus reaction mechanisms has produced intriguing suggestions that truly multi-nucleon interactions do occur. They are the subject of this talk. To develop this subject I will focus on reactions that cannot happen at all without the essential participation of two or more nucleons.

The simplest of these reactions is inclusive double charge exchange (DCX), which is commonly thought to proceed as two successive quasi-free single-charge-exchange (SCX) reactions. At a minimum, the charges on two like nucleons must be changed for this reaction to occur. It is not a very probable reaction, contributing only about 1 percent to the total reaction cross section. Nevertheless, there is an extensive collection of observations of this reaction in nuclei ranging in A from 3 to 208. The systematics of the total cross sections derived from these observations is my first example.[1-4]

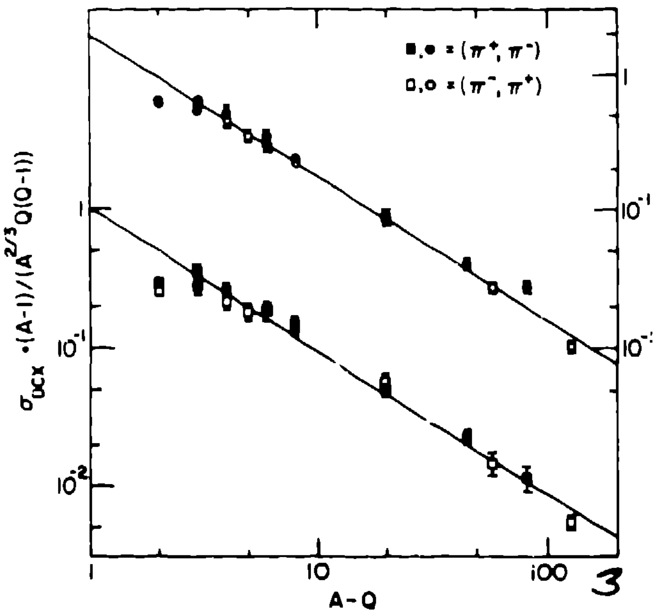
Figure 1 presents the variation of the cross sections of the reaction $A(\pi^+,\pi^-)X$ with A at incident energies of 180 and 240 MeV. The monotonic rise of the cross section according to a power law in A is not unexpected, but observe that the cross sections for ^{7}Li and ^{9}Be, which have "extra" neutrons with which the π^+ interact to produce double charge exchange, deviate significantly, lying about a factor of two above the general trend. The surprising result is in Fig. 2. The cross section for the $A(\pi^-,\pi^+)X$ reaction, which singles out the protons, rises approximately parallel to that for the



(π^+,π^-) reaction up to about A = 40, where it becomes constant and remains so up to A = 208, despite the fact that Pb has over four times as many protons as Ca.

A possible explanation of the observed "saturation" of the (π^-,π^+) cross section is that the large neutron excess in heavy nuclei shields the protons from the incoming negative pions. At Δ-resonance energy negative pions interact more strongly with neutrons than with protons, but it is the protons on which (π^-,π^+) takes place. Therefore, the (π^-,π^+) process is inhibited by competing reactions that occur on the neutrons. It is an interesting accident of Nature that the resolution of this competition results in a cross section with zero slope for A > 40. Naturally neutrons and protons exchange roles for positive incoming pions, but since there are no heavy proton-rich nuclei, the (π^+,π^-) cross section does not "saturate" at some value of A.

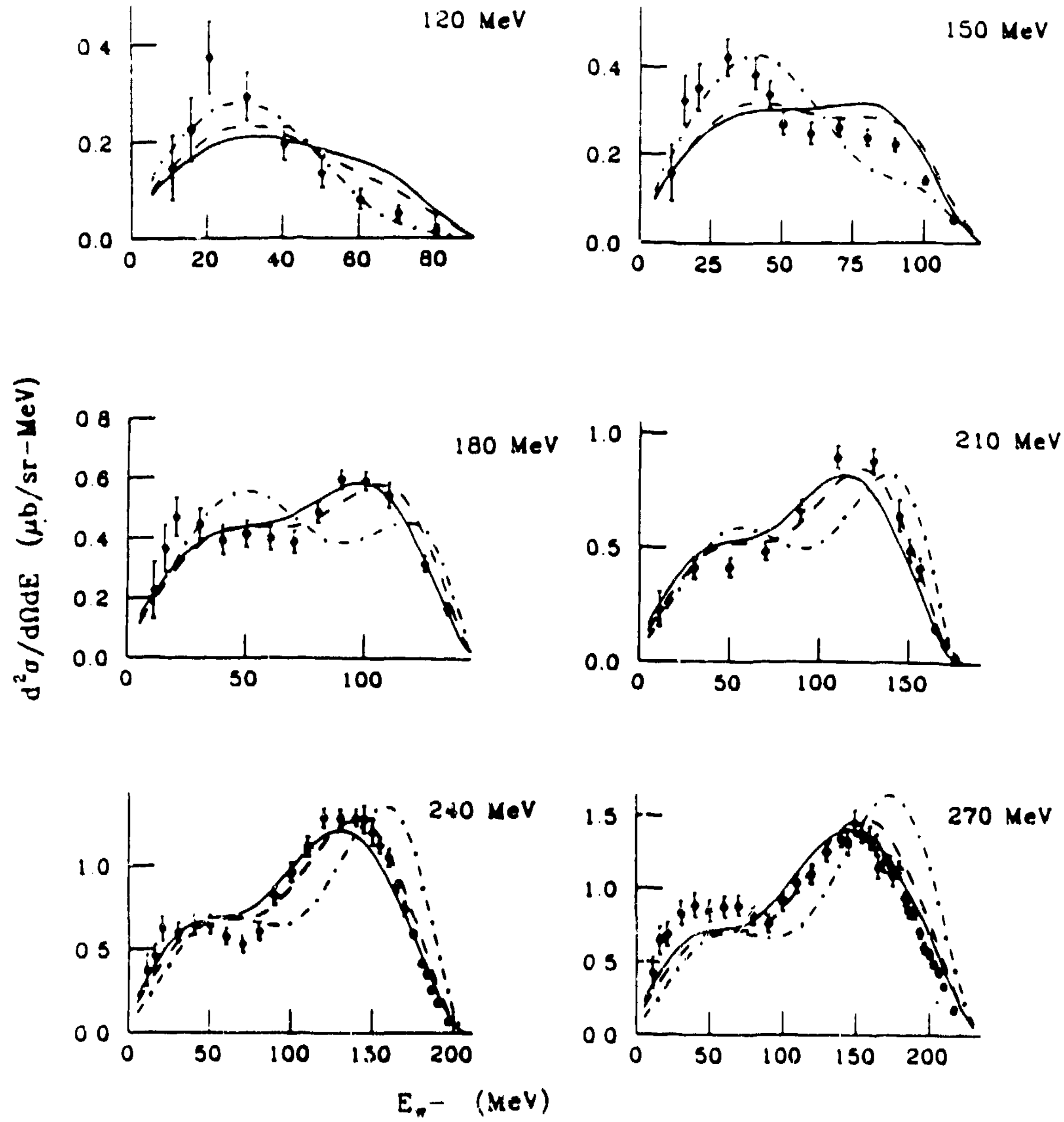
A heuristic scaling rule has been developed to test these simple ideas.[1] A negative pion, for example, running the gauntlet of competing reactions, would have a probability proportional to Z/N of completing the first SCX, and the intermediate neutral pion, which interacts equally with protons and neutrons, would have a probability proportional to (Z-1)/(A-1) of completing the second. The overall probability that a negative pion will produce a double charge exchange reaction would therefore be proportional to the product Z(Z-1)/N(A-1). To describe both the (π^+,π^-) and the (π^-,π^+) reactions in the same context, we define Q to be the number of nucleons of the species appropriate to the incident pion; A-Q is then the number of spectator nucleons on which competing reactions take place. The projected area of a nucleus varies as $A^{2/3}$. Therefore, the total reaction cross section for double charge exchange should depend on the population of nucleons in a nucleus as $A^{2/3}Q(Q-1)/(A-Q)(A-1)$.



caption on side

We have tested this rule by dividing the total reaction cross sections by $A^{2/3}Q(Q-1)/(A-1)$ and plotting these ratios against (A-Q). Figure 3 displays the results for both the (π^+,π^-) and (π^-,π^+) reactions at 180 and 240 MeV. In these graphs cross sections for both charges of incident pion occur at the same values of (A-Q) for N=Z nuclei but at different values of (A-Q) for N > Z nuclei. This simple rule adequately describes all of the cross sections at a particular energy, including those for ^{7}Li and ^{9}Be, and it succeeds in reconciling the quite different behaviors of the (π^+,π^-) and (π^-,π^+) reaction cross sections. The properties of the nucleus, not even the fact that is a bound system, appear to have no influence on the behavior of these cross sections. In this picture, the reaction would occur in the same way on a collection of the appropriate kind of marbles in a basket, but the importance of competition among possible reactions has been exhibited.

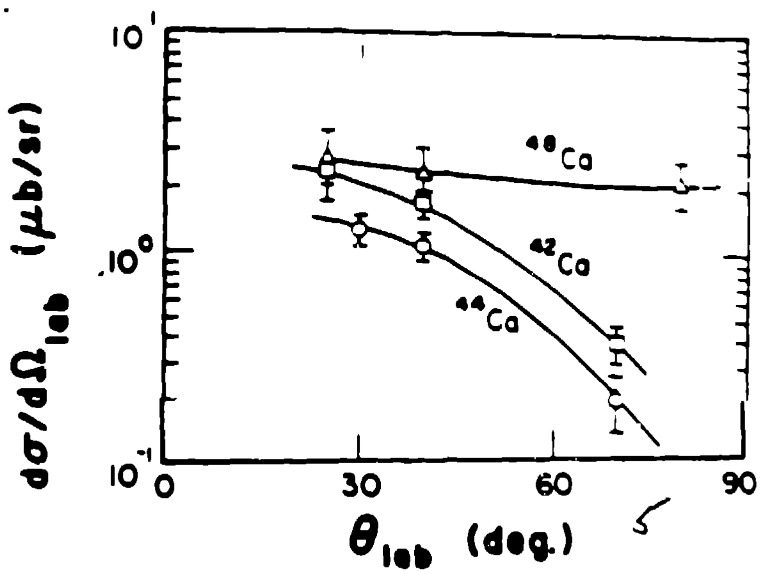
However, when we look at the inclusive DCX reaction in more detail, specifically at the doubly differential cross sections for DCX in ^{4}He at 25° (Fig. 4), we see, at incident energies of 180 MeV and greater, an intriguing double peak that begs for explanation.[5] The origin of this structure is thought to be the reaction mechanism itself. At these energies, the differential cross section for single charge exchange with a free nucleon is strongly peaked towards large and small angles. Thus, in the sequential single charge exchange scatterings that result in double charge exchange, the most probable sequences that produce a pion at a forward angle are two small angle scatterings in which rather little energy is lost, or two large angle scatterings in which considerable energy is transferred to two nucleons. The two peaks in the doubly differential cross section are thought to be populated by pions following these two scattering sequences.



This qualitative explanation has been tested analytically by comparison with a semi-classical calculation of the sequential scattering process.[6] In this calculation pions propagate as plane waves, both before and between scatterings, the nucleons are bound by a constant average potential, and the scattering probabilities are governed by the free πN t-matrix. The free pion-nucleon t-matrix is evaluated at an energy determined both by the Fermi momentum of the struck nucleon and the energy the pion retains after any previous scattering. Spin and antisymmetrization of the nucleon wave functions are ignored, because the struck nucleons will be ejected from the nucleus, but the momentum of the struck nucleon is forced to lie above the Fermi surface. The several curves in Fig. 4 are predictions of this model for several values of the average nuclear potential: solid line, -55 MeV, dashed line, -37 MeV, dot-dashed line, 0 MeV. This semi-classical calculation, for all its simplifications (it was quite difficult enough for all of that) doesn't do badly. The shape of the doubly differential cross section is quite nicely reproduced for an average binding energy of -55 MeV. Both the calculation and the data reflect the changing character of the free πN interaction that drives inclusive DCX. I won't show it, but if the angular dependence of the πN amplitude is made isotropic, the doubly peaked structure of the cross section disappears at all energies, as expected. Of more interest in the context of our pursuit of multi-nucleon mechanisms however, is the influence of the average nuclear potential: a non-interacting collection of nucleons would not produce a cross section of the observed shape.

Next we consider the exclusive double charge exchange reaction in which the final state is the double isobaric analog of the target nucleus. The reaction mechanism is still thought to be sequential single charge exchange, but the experimental insistence that the analog final state be formed limits the selection of nucleons that can participate to those occupying specific states. For example, in the (π^+,π^-) reaction on the isotopes of calcium, ^{42}Ca, ^{44}Ca and ^{48}Ca, two "valence" neutrons, occupying orbitals outside the closed-shell N=20 Z=20 core are changed into protons, without changing their wave functions in any other way, to produce the analog isotopes of titanium. Now, if we were to predict the ratios of cross sections for the (π^+,π^-) reaction among the three calcium isotopes in the same naive way that worked so well for the inclusive reaction, we would simply count up the total number of valence neutron pairs in each nucleus and arrive at the suggestion that ^{48}Ca should have a cross section 28 times that of ^{42}Ca. Observation of the exclusive reaction at 35 MeV does not bear this out, as shown dramatically in Fig. 5. The cross sections for ^{48}Ca and ^{42}Ca are about equal, while that for ^{44}Ca is a bit smaller.[7] There are surely no factors of 28 to be seen. What is going on?

We have come upon a quintessentially quantum mechanical effect. In a sequential process such as this that is forced by experimental choice to lead to a definite final state, the spatial correlation of the participating neutrons becomes particularly important.[8] The wave functions of the valence neutrons have the property that states with fewer neutrons exhibit greater spatial correlation. The effect of the enhanced correlation in ^{42}Ca, where only two neutrons are present, overrides the greater opportunity for scattering afforded by a larger number of less strongly correlated neutrons in the heavier isotopes. The slightly depressed value for the ^{44}Ca cross section, as well as the shape of the angular distribution may be understood in these terms as well. In fact, these cross sections are thought to be so strongly driven by the exact nature of the wave functions, that low-energy exclusive DCX measurements might well lead to refined knowledge of nuclear structure. At a minimum we have finally sighted the elusive two-body correlation in nuclei.



In the sequential SCX picture of double charge exchange, the successive scatterings themselves, whatever other effects enter into the process, may be thought of as effectively free. Pion absorption, on the other hand, cannot happen on a free nucleon, and the (π,p) reaction in nuclei is suppressed to a tiny fraction of the total reaction cross section by the momentum mismatch incurred in imparting the total energy of the pion to a single nucleon. However, pions are strongly absorbed by deuterons, perhaps unexpectedly so in view of the weak binding of this simplest of nuclei. The cross section for the πd --> pp reaction is about 12 mb at 150 MeV of incident energy, and its energy dependence clearly suggests the participation of the Δ-resonance. In a simple picture of the reaction, the incoming pion scatters far off the mass shell from one of the nucleons to be absorbed by the other. To explain the magnitude and energy dependence of the cross section it is assumed that a delta is formed in the initial scattering and that a short range interaction between the delta and the other nucleon exists that can supply the momentum necessary to produce two free nucleons in the final state.

This elementary absorption process is not fully understood at present, but pion absorption by apparently deuteron-like two-body systems within nuclei is distinctly visible in the kinematical behavior of the cross section even in heavy nuclei. It is equally apparent, however, that this two-body absorption does not exhaust the cross section of the reaction. Studies of pion absorption have therefore been inspired by two preoccupations. First, extraction of the two-body component to see if study of absorption involving nn or pp pairs of nucleons will shed light on the mechanism at work in two-body absorption, and second, to assess the remainder of the cross section for contributions from three and four body processes. Unfortunately, strongly interacting as they are, the incoming pions may very well scatter from one nucleon and then go on to be absorbed by another pair, or the nucleons that absorbed the pion may scatter on their way out of the nucleus. These potentially commonplace nuclear processes are not regarded as "real" three or four body interactions but it is no easy matter to distinguish between the interesting and prosaic processes experimentally.

An example of the first preoccupation is the measurement of absorption by ^3He of both positive and negative pions.[9] In ^3He observation of two outgoing nucleons, as has been accomplished in this experiment, completely determines the final state. The results are displayed in the form of Dalitz plots (Fig. 6-7). The band is defined by the acceptance of the detectors, the density of points is proportional to the square modulus of the matrix element of the reaction, but it is hard to judge the shape from above.

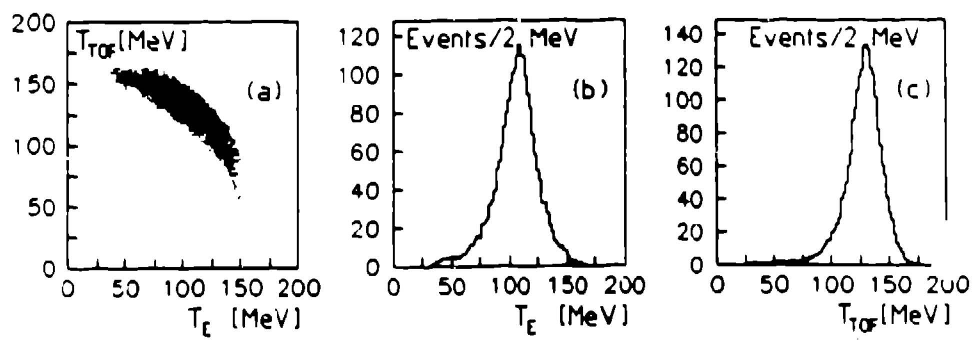


Fig. 8. (a) Dalitz plot for $^3He(\pi^+, pp)p$. (b) Projection on the energy axis T_E. (c) Projection on the energy axis T_{TOF}.

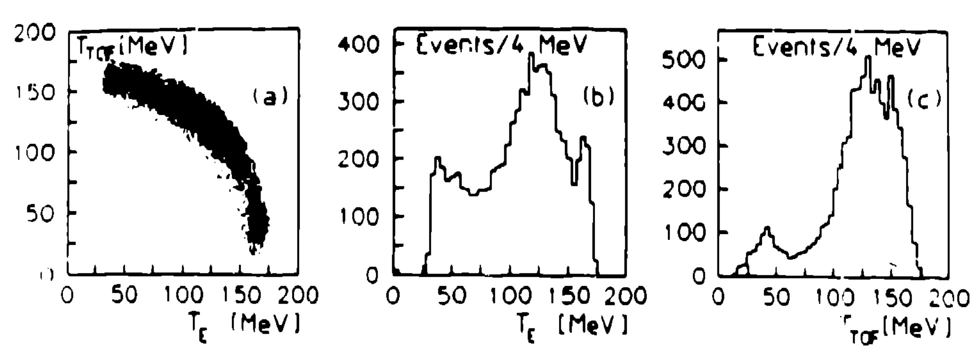
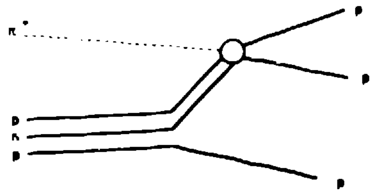
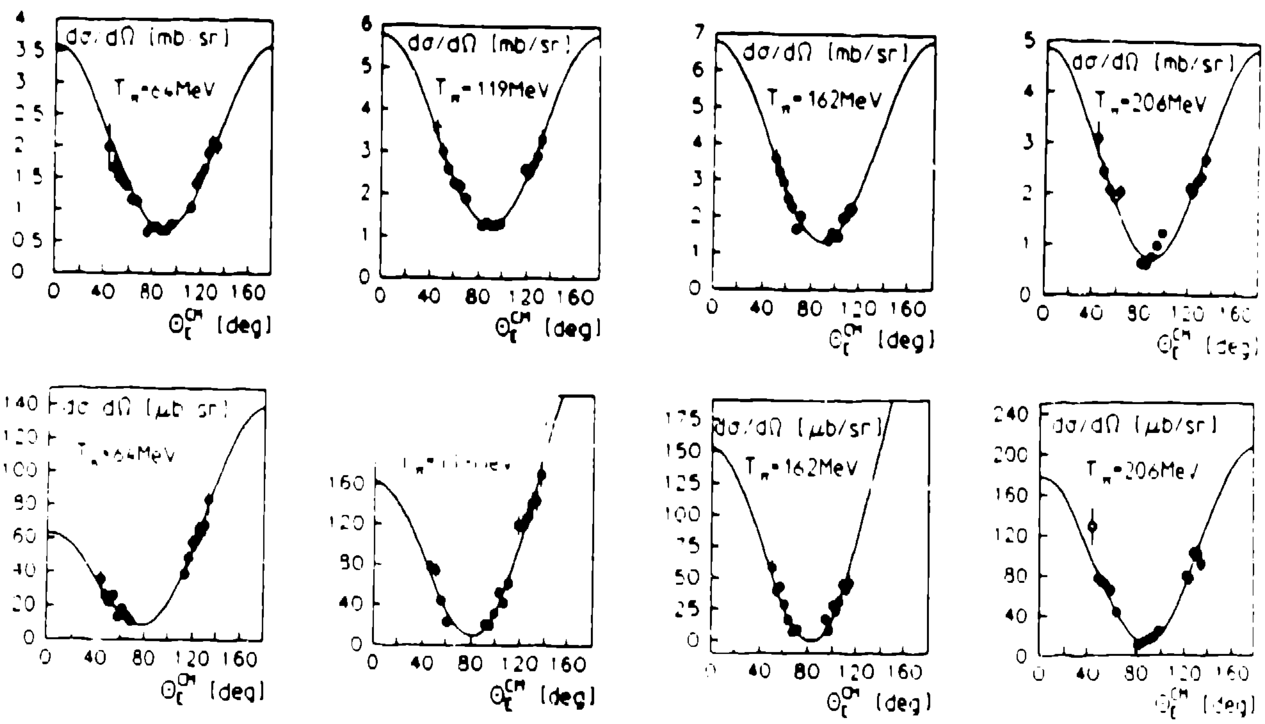


Fig. 9. (a) Dalitz plot for $^3He(\pi^-, pn)n$. (b) Projection on the energy axis T_E. (c) Projection on the energy axis T_{TOF}.

The projections are more suggestive: in the (π^+, pp) reaction one sees virtually only the quasi-free πd absorption peak, but in the (π^-,pn) reaction there are quite visible peaks at the low and high energy ends of the distributions that suggest the participation of final state interactions.

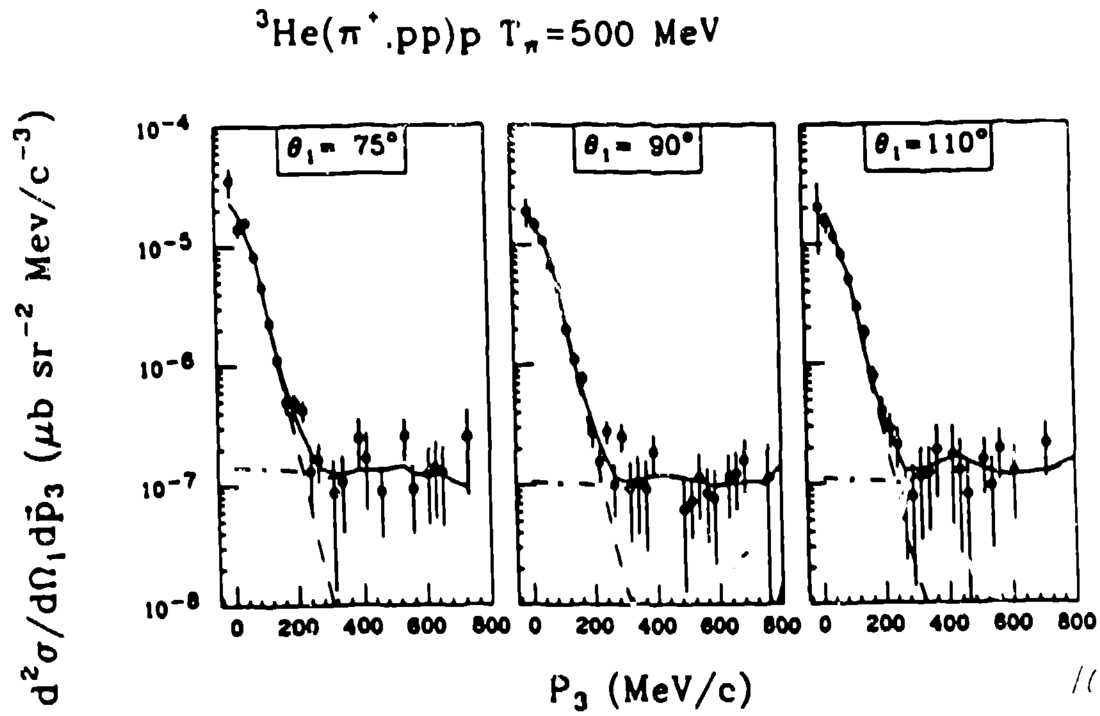


Absorption by a two-body system within ^{3}He is depicted by the diagram in Fig. 8. The internal momentum of the two-body system is equal and opposite to that of the remaining nucleon. This diagram is thought to be a useful description of absorption events in which this spectator nucleon is given a small momentum. Thus the two-body contribution to the reaction may be identified by selecting events in which the undetected nucleon was found to have small momentum. The center of mass angular distributions of the two-body absorption cross section are shown in Fig. 9.[9]



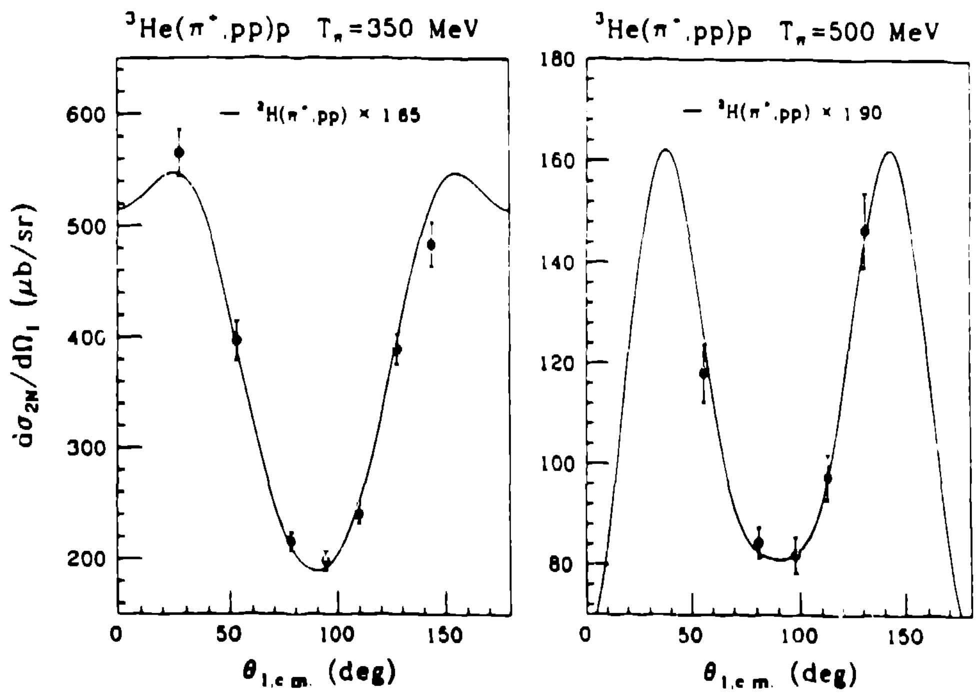
We see that these are not the same for the pp and the np final states. First of all, the cross section for producing the np final state is over an order of magnitude smaller. The angular distribution of the pp final state must, of course, be symmetric about $\pi/2$, whereas the np final state does not have to be, and it isn't. The smooth curves are Legendre polynomial fits to the data. At the two lowest energies the angular distribution of the pp final state is indistinguishable from that belonging to the free $\pi d \rightarrow pp$ reaction after its magnitude is scaled by a factor of 1.5, which is the "number of deuterons" one expects from isospin arguments to find in ^3He. At the two higher energies the scaling factor appears to be the same, but the data do not extend to small and large enough angles to test the match to the free angular distribution.

As the energy of the incident pions is increased, the two-body process continues to be the most prominent feature of the reaction. With so much of the cross section taken up by the expected two-body process, how can we search for three-body effects? As seemingly wrong-headed as it may at first seem, a useful method is to bin the data in $p_3^2 dp_3 d\Omega_3$, the momentum and solid angle of the undetected particle. The effective acceptance of the apparatus for the undetected particle is defined by the detectors of the other two, and, conveniently, does not have a low energy cutoff. Differential cross sections constructed by this procedure are shown in Fig. 10.[10]



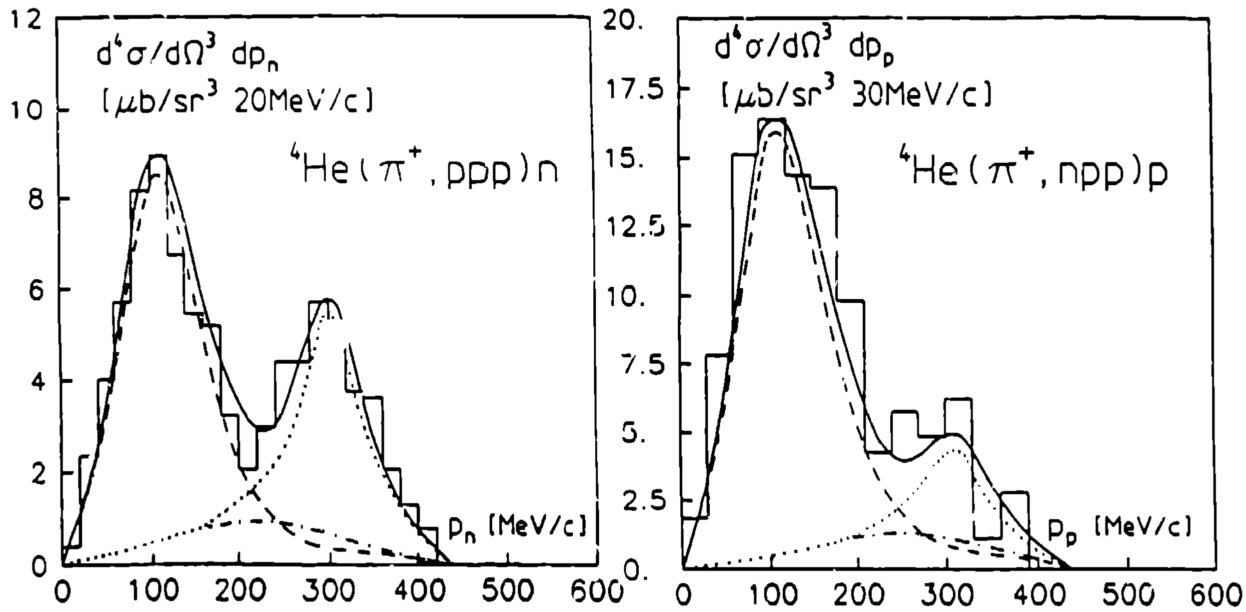
Roughly speaking, the steeply falling portion of the curves represents the two-body absorption cross section modulated by the momentum distribution of the spectator proton in ^3He. As the probability of finding higher momentum protons in ^3He declines, a flat region of the cross section is uncovered that seems clearly to result from some other process. This slowly varying part of the cross section is found to follow the shape of the distribution in phase space of events in which three nucleons randomly share the total energy of the incoming pion, suggesting that the matrix element for this process is rather constant. Extraction of a cross section for the three-body process is rather model dependant, but its presence has been clearly revealed.

Angular distributions of the two-body contribution to the cross sections have been constructed by integrating over the low momentum, steeply falling regions of the data shown in Fig. 10. These are compared with those of the free $\pi d \to pp$ reaction in Fig. 11.[10] Here, the scale factors, 1.65, and 1.9 are somewhat larger than the value 1.5 found at lower energies (and expected from isospin arguments), leading to the suggestion that the np pairs found in ^3He are more compact than free deuterons. Experiments are planned that will extend the angular ranges of these measurements to see if absorption on "bound deuterons" really follows the bending over of the angular distribution at large angles characteristic of absorption by free deuterons.[11]



11

A triple coincidence measurement of pion absorption in ^4He has been performed.[12] In this experiment the 3 detectors were arranged at angles chosen to avoid the regions of phase space populated by events from the dominant quasi-free two-body process. Both the (π^+,ppp)n and the (π^+,npp)p reactions were observed. Once again the cross sections may be displayed in terms of the momentum of the undetected nucleon (Fig. 12).



We clearly see two peaks in these distributions. To explain them we must do some modeling. Imagine that the low energy peak is due to a quasi-free three-nucleon process. Then the unobserved nucleon against whose momentum we're plotting is a spectator, but we know the momentum distribution of a single nucleon in ^{4}He from electron scattering measurements. Using this knowledge, it is possible to simulate the three-nucleon process for the particular geometry of the experiment (assuming a constant matrix element). This simulation is shown as the dashed lines in the figure. The agreement is not bad at all. A four-nucleon mechanism with constant matrix element would produce the phase space controlled distribution suggested by the dash-dotted line. Events in the high energy peak are characterized by small momentum difference between an observed proton and the unobserved neutron in the (π^+,ppp)n reaction so this peak is identified as a pn final state interaction, but note its importance; it is not a small effect compared to the three-body process. In the distribution of the (π^+,npp)p reaction the quasi-free three-nucleon process is more important, and the final state interaction between two protons is, not surprisingly, suppressed.

We have at last identified a peak in a cross section that may with some confidence be attributed to a three-body absorption mechanism, but only at one incident energy, and in one carefully arranged experimental geometry. Delineating the systematics of this fascinating reaction mechanism would be difficult and time consuming with the conventional apparatus employed to get this far. Imagine what we will learn about multi-nucleon reaction mechanisms when we are able to make kinematically complete measurements of this kind rapidly enough to permit systematic exploration of this and other phenomena that are coming to light.

This brings me to my conclusion. Far from being the mined out field of endeavor its detractors have sometimes claimed, pion-nucleus physics has come upon the rich lode that prospectors have always suspected was there. To mine it, we will need more sophisticated equipment; and it is being developed. Detectors such as LADS, CHAOS, and the BGO ball provide for the detection of charged particles with good energy resolution over nearly all of 4π steradians. With these detectors we may begin the systematic exploration of the multi-nucleon phenomena that are the natural property of pion-nucleus reactions.

REFERENCES

1) P. A. M. Gram et al., Phys. Rev. Lett. 62, 1837 (1989).

2) J. L. Matthews, in: Proceedings of the LAMPF Workshop on Pion Double Charge Exchange (Los Alamos National Laboratory Report No. LA-10550-C, 1985), and in: The Second International Workshop on Pion Double Charge Exchange, Los Alamos, NM, 1989 (World Scientific, Singapore in press).

3) P. A. M. Gram, in: Pion-Nucleus Physics: Future Directions and New Facilities at LAMPF, Los Alamos, New Mexico, 1987, eds. R. J. Peterson and D. D. Strottman, AIP Conference Proceedings No. 163 (American Institute of Physics, New York, 1988), p. 79.

4) S. A. Wood et al., Phys. Rev. Lett. 54, 635 (1985).

5) E. R. Kinney et al., Phys Rev. Lett. 57, 3152 (1986).

6) E. R. Kinney, Los Alamos National Laboratory Report No. LA-11417-T.

7) H. W. Baer, in: Intersections Between Particle and Nuclear Physics, Rockport, Maine, 1988, ed. G. M. Bunce, AIP Conference Proceedings No. 176 (American Institute of Physics, New York 1988), p. 589.

8) E. Bleszynski et al., Phys. Rev. Lett. 60, 1483 (1988).

9) P. Weber et al., Nuclear Physics A501, 765 (1989).

10) L. C. Smith et al., Phys. Rev. C40, 1347 (1989).

11) L. C. Smith and R. C. Minehart, spokesmen, LAMPF Research Proposal No. 1126, 1988 (unpublished).

12) G. Backenstoss et al., Phys. Rev. Lett. 61, 923 (1988). M. Steinacher et al., Paul Scherrer Institut Report PR-90-04, 1990.

Fig. 1. Total inclusive cross sections for the $A(\pi^+,\pi^-)$reaction at 180 Mev (solid squares) and 240 MeV (solid circles) as functions of A. (From Ref. 1).

Fig. 2. Total inclusive cross sections for the $A(\pi^-,\pi^+)$reaction at 180 Mev (open squares) and 240 MeV (open circles) as functions of A. (From Ref. 1).

Fig. 3. Total inclusive cross sections at 240 MeV (upper points and line, right-hand scale) and 180 MeV (lower points and line, left-hand scale), multiplied by $(A-1)/A^{2/3}Q(Q-1)$ plotted against A-Q, where Q=N for (π^+,π^-) and Q=Z for (π^-,π^+). The ratios for nuclei with $A \geq 6$ are fitted by a power law whose dependence is found to be $(A-Q)^{-1.04\pm0.03}$, close to the predicted value, at both incident energies. (From Ref. 1).

Fig. 4. Doubly differential cross sections for the $^4He(\pi^+,\pi^-)4p$ reaction at 25^o in the laboratory for incident energies of 120, 150, 180, 210, 240 and 270 MeV. The curves are explained in the text. All of the predictions have been normalized to yield the same integrated area as that of the measured cross sections. (From Ref. 6).

Fig. 5. Preliminary double-isobaric-analog-state-formation cross sections in the calcium isotopes at 35 MeV. (From Ref. 7).

Fig. 6. Dalitz plot and projections on the two axes for the $^3He(\pi^+,pp)p$ reaction at 119 MeV. (From Ref. 9).

Fig. 7. Dalitz plot and projections on the two axes for the $^3He(\pi^-,pn)n$ reaction at 119 MeV. (From Ref. 9).

Fig. 8. Pion absorption by a two body system in ^3He.

Fig. 9. Angular distributions of two-nucleon events in the $^3He(\pi^+,pp)p$ (a) and $^3He(\pi^-,pn)n$ (b) reactions at incident energies of 64, 119, 162 and 206 MeV. The curves are Legendre polynomial fits to the data. (From Ref. 9).

Fig. 10 Recoil momentum distributions of the $^3He(\pi^+,pp)p$ reaction at 500 MeV at three laboratory angles. Dashed line is a PWIA fit to the two-body (steeply falling) component; dotted line is three-body phase space. (From Ref. 10.).

Fig. 11 Angular distributions of the two-body absorption component of the $^3He(\pi^+,pp)p$ reaction at 350 and 500 MeV compared to the free $\pi d \to pp$ cross sections multiplied by factors of 1.65 and 1.90, respectively. (From Ref. 10.).

Fig. 12. Differential cross section as a function of the momentum of the undetected neutron in $^4He(\pi^+,ppp)n$ (a) and the undetected proton in $^4He(\pi^+,npp)p$ (b). Histogram: data; dashed line: simulation of three nucleon mechanism; dotted line: simulation of four-nucleon mechanism plus final state interaction; dashed-dotted line four-nucleon mechanism only; solid line: sum. (From Ref. 12).