PION–NUCLEUS PHYSICS WITH THE CHAOS DETECTOR AT TRIUMF*

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A concise description of the experiments that make up the CHAOS program at TRIUMPF site is presented.

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1. Introduction

Construction of the CHAOS detector at TRIUMF was completed in 1992, with commissioning runs taking place on the M11 channel in late 1992 and early 1993. The first physics data was taken in July of 1993, and an active experimental program has been ongoing ever since. The project was headed by G.R. Smith and P.A. Amaudruz. Other members of the CHAOS collaboration come from the following institutions: TRIUMF, the University of British Columbia, INFN and the University of Trieste, the University of Regina, the University of Melbourne, the University of Colorado, the University of Karlsruhe, California State University in Sacramento, and most recently, the University of Tubingen.

CHAOS is a unique magnetic spectrometer designed for studies of pion induced reactions. It is based on a cylindrical dipole magnet, producing vertical magnetic fields of up to 1.6 T. The scattering target is located in the center of the magnet. Charged particle tracks produced by pion interactions are identified using four concentric cylindrical wire chambers which surround the target. Particle identification and track multiplicity are determined by cylindrical layers of scintillation counters and lead-glass Cerenkov counters, which form the CHAOS Fast Trigger (CFT) system. A sophisticated and flexible second level trigger system, based on the PCOS readout of the inner three wire chambers, allows for background rejection and selection of events from processes with small cross sections, at incident

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pion fluxes in excess of 5 MHz. CHAOS subtends 360° in the horizontal plane, and ±7° out of this plane, leading to a solid angle coverage of $\sim 10\ /4\pi$ sr. Further details can be found in Ref. [1].

A brief description of the experiments which make up the CHAOS program is given below, listed by TRIUMF experiment number:

E560: Measurement of analyzing powers in low energy $\pi^{\pm}\vec{p}$ scattering. The results from this experiment will make possible a more precise determination of the low energy πp scattering amplitudes. This will help resolve the existing difficulties in the πN database, arising from conflicting $d\sigma/d\Omega$ measurements. More importantly, it will improve the accuracy with which the $\pi N\ \Sigma$ term can be determined, and consequently, the $s\bar{s}$ content of the proton. Data above 67 MeV were acquired in 1995. The more interesting lower energy region from 30 to 70 MeV is scheduled to receive beam in the summer of 1996.

E624: Study of the elementary $H(\pi^-,\pi^+\pi^-)n$, $H(\pi^-,\pi^+\pi^0)p$, $H(\pi^+,\pi^+\pi^+)n$, and $H(\pi^+,\pi^+\pi^0)p$ reactions from $T_\pi = 220$ to 300 MeV. One goal of these measurements is to improve the values of the s-wave isospin 0 and 2 $\pi\pi$ scattering lengths, which are predicted within the framework of chiral perturbation theory. In addition, the data should permit the extraction of $\pi\pi$ scattering amplitudes, phase shifts, and cross sections as a function of energy. Data analysis is nearing completion.

E653: Measurement of the $(\pi^+,\pi^+\pi^{\pm})$ pion-induced pion production reaction on a series of nuclear targets (^{2}H, ^{12}C, ^{40}Ca, and ^{208}Pb) at $T_\pi = 280$ MeV. Data taking is complete. Analysis has revealed that the $\pi^+\pi^-$ invariant mass distribution near threshold is close to zero for A = 2, and increases dramatically with increasing A; unlike the $\pi^+\pi^+$ invariant mass distribution, which has some strength near threshold regardless of A. First results have been submitted for publication [2], and further analysis is continuing.

E719: Measurement of the $^4He(\pi^+,\pi^-pp)$ reaction using a ^{4}He gas target. This is a search for the hypothetical d' dibaryon ($J^P = 0^-$, M = 2.06 GeV) which has been put forward as the explanation for an enhancement in the total cross section of nuclear pion double charge exchange (DCX) at low energies [3]. A bump in the π^-pp invariant mass spectrum at the right energy would provide a model-independent confirmation of the existence of the d'. Some data were taken in January of 1996, and more running is planned for the spring and summer.

E721: Study of the two-body reaction $\pi d \to \Delta N$ with the goal of testing new unified predictions of the πNN system. Complete angular distributions of the Δ production will be obtained from the appropriate subset of the $\pi d \to \pi NN$ phase-space by reconstruction of the Δ decay products. In addition, Δ polarizations will be measured for the first time, from the asymmetries in the angular distributions of the decay products. Data taking for this experiment has been completed at $T_\pi = 140$ and 256 MeV.

E725: Measurement of the ^{4}He(π^+,π^-) reaction at $70 < T_\pi < 120$ MeV, using a liquid ^{4}He target. Unlike more conventional calculations, DCX calculations including the hypothetical d' dibaryon (see E719 above) predict a sharp rise in the cross section above the d' threshold ($\sim$ 85 MeV). The few existing data in this energy region suffer from large error bars or large systematic uncertainties, and thus this experiment was performed early in 1996. Preliminary online results indicate a behavior consistent with the predictions which include the d'.

2. E722 and E723

In TRIUMF experiments 722 and 723, we have simultaneously measured ^{12}C(π^+,pp), ^{12}C(π^+,ppp), and all other reactions with two or more charged particles in the final state, following the interaction of π^+'s with ^{12}C, at incident pion energies of 280, 240, and 200 MeV. A cylindrical plastic scintillator, 6 mm in diameter, was used as an active ^{12}C target, and also provided a source of πp elastic scattering events which were used to check normalizations and calibrations. The threshold for detected protons was $\sim$ 200 MeV/c (limited by energy loss in the target), and the momentum resolution was $\Delta p/p \sim 1.5$ %. In the part of the data set that has been analyzed to date, the threshold for detected pions was $\sim$ 145 MeV/c. At momenta below this value, the trajectories inside CHAOS curved by more than 180°, and could not be reconstructed reliably. The threshold is considerably smaller for other parts of the data set, which were run with lower settings of the CHAOS magnetic field. Fig. 1 shows a typical (π^+,ppp) event. The three outgoing proton trajectories were reconstructed from the hits (indicated as $\times$'s on the figure) in the four CHAOS chambers. Note that CFT blocks were removed, and the drift chambers WC3 and WC4 were turned off, in the region of the incident and outgoing beam. The incoming beam was reconstructed from hits in the proportional chambers WC1 and WC2.

The solid line in Fig. 2 shows the distribution of the sum of kinetic energies (TSUM $= T_{p_1} + T_{p_2}$) of the two detected protons from the (π^+,pp) reaction at $T_\pi = 280$ MeV. The solid lines in Fig. 3 illustrate the missing momentum ($p_{\rm missing} = |\vec{p}_\pi - \sum \vec{p}_{p_i}|$) distributions calculated for these events, on an event-by-event basis, for three different regions of TSUM: (a) is for TSUM > 370 MeV, and is consistent with the vector sum of the Fermi momentum of two uncorrelated p-shell nucleons. (b) is for $200 <$ TSUM < 310 MeV. The large amount of missing momentum here is an indication that at least one additional undetected nucleon must have participated in

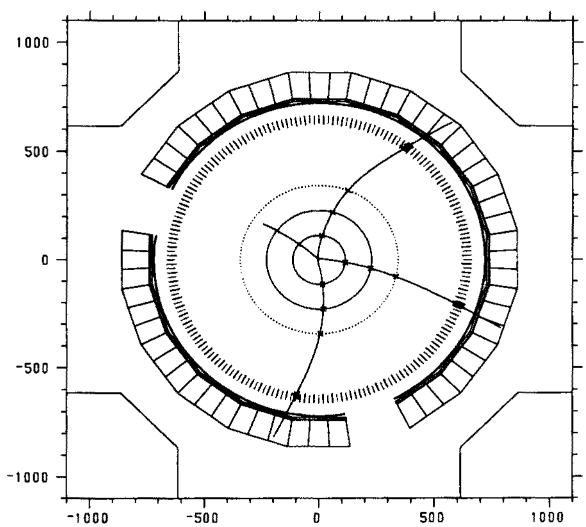

Fig. 1. Typical (π^+, ppp) event, illustrating the various components of the CHAOS detector. The pion beam is incident from the left, and reconstructed from the hits in the two innermost chambers. The scale is in mm.

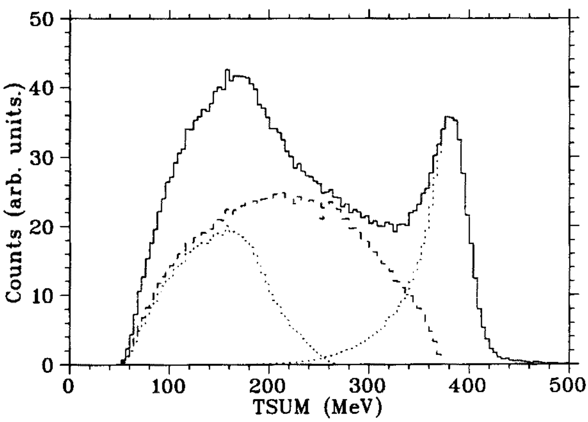

Fig. 2. The solid line represents the summed kinetic energies of the two protons detected in the $^{12}C(\pi^+, pp)$ reaction at $T_\pi = 280$ MeV. See text for an explanation of the dashed lines.

the absorption process. (c) is for TSUM < 160 MeV. To aid in the interpretation of this distribution, we note that at this low value of TSUM, the pion has not necessarily been absorbed. The short-dashed curve in (c) indicates p_{missing} calculated from the two protons from the $(\pi^+, \pi^+ pp)$ reaction, which was measured simultaneously in this experiment. The long-dashed curve indicates p_{missing} calculated from (π^+, ppp) events (also measured simultaneously) by considering only two of the three detected protons at a time. It is clear that the sum of the short and long-dashed lines describes the solid line very well.

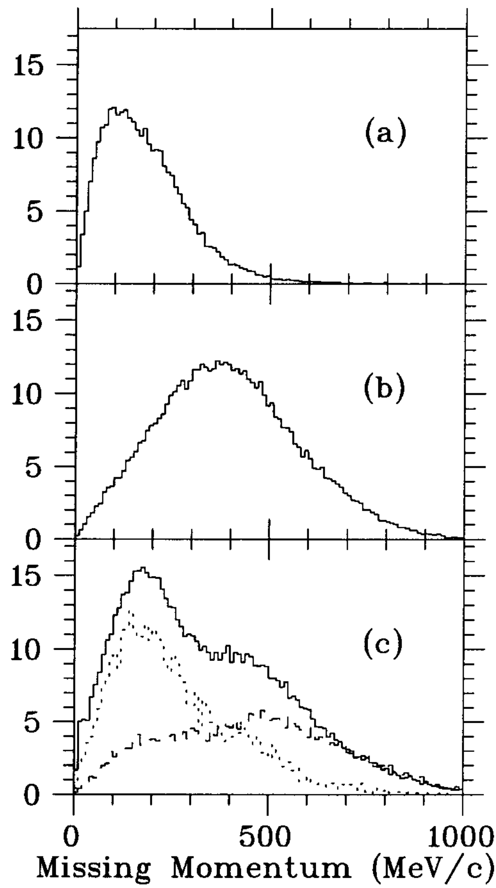

Fig. 3. Missing momentum distributions for the (π^+, pp) events shown in Fig. 2, with TSUM > 370 MeV in (a); 200 < TSUM < 310 MeV in (b); and TSUM < 160 MeV in (c). See text for an explanation of the dashed lines in (c).

In fact, the relative normalizations of the short and long-dashed curves in Fig. 3c have been adjusted by fitting to the solid line, and the areas under the curves allow us to determine the relative contributions of two-nucleon knockout and multi-nucleon absorption to the (π^+, pp) spectrum. By performing a similar analysis of the p_{missing} distributions for smaller bins in

TSUM, we can obtain a systematic decomposition as a function of TSUM. Similarly, at higher values of TSUM, we can estimate the relative contributions of two-nucleon and multi-nucleon absorption by fitting the $p_{missing}$ distributions with a sum of shapes corresponding to the two processes. The shape for two-nucleon absorption can be fixed to the one shown in Fig. 3a, while the shape for multi-nucleon absorption can be taken from an analysis of (π^+, ppp) events. The results are shown in Fig. 2, where the short-dashed lines at low TSUM illustrate the contribution from multi-nucleon knockout, the short-dashed lines at high TSUM show the contribution from two-nucleon absorption, and the long-dashed lines indicate the events that can be attributed to multi-nucleon absorption.

If we consider only those (π^+, pp) events with TSUM > 370 MeV, we find that their angular distribution (i.e. $d\sigma/d\Omega$) is very similar in shape to that of the elementary $\pi d \rightarrow pp$ reaction. We can estimate a total cross section for two-nucleon absorption by integrating $d\sigma/d\Omega$, and correcting for the number of two-nucleon events with TSUM < 370 MeV. Our preliminary result for σ obtained in this way is 5.1 mb at $T_\pi = 280$ MeV. A similar analysis at $T_\pi = 240$ and 200 MeV gives the very preliminary results of 7.9 mb and 9.0 mb, respectively.

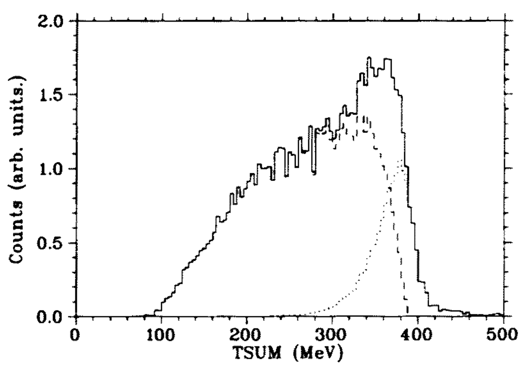

Fig. 4. The solid line represents the summed kinetic energies of the three protons detected in the $^{12}C(\pi^+, ppp)$ reaction at $T_\pi = 280$ MeV. See text for an explanation of the dashed lines.

The solid line in Fig. 4 again shows a TSUM distribution, this time for the three protons from the (π^+, ppp) reaction. The solid line in Fig. 5 shows the missing momentum distribution for those events with TSUM > 320 MeV, while the dashed line is for events with TSUM < 320 MeV. The large amount of missing momentum for the latter indicates that at least one additional undetected nucleon must have been involved in the reaction. As for the case of (π^+, pp), we can attempt to distinguish between

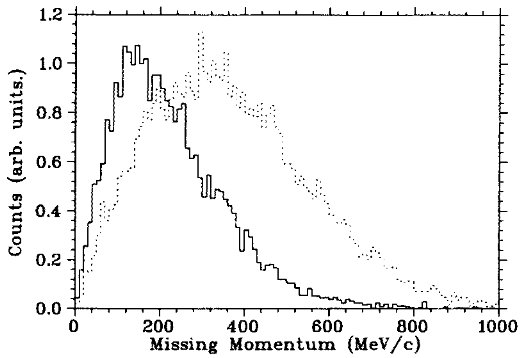

Fig. 5. The solid line represents the missing momentum calculated for the (π^+, ppp) events shown in Fig. 4, with TSUM > 320 MeV (solid line) and TSUM < 320 MeV (dotted line).

events in which only three nucleons participated, and events in which more than three nucleons participated by fitting p_{missing} distributions for various TSUM bins. For the former, we take a fixed shape from the actual (π^+, ppp) data at the highest TSUM. For the latter, we used used the shape from a phase-space model calculated assuming four-nucleon absorption with a spectator residual nucleus. The results of this model provided an excellent description of p_{missing} at low values of TSUM. The results of the fits are shown in Fig. 4, where the short-dashed line indicates those events in which p_{missing} is consistent with three participating nucleons, and the long-dashed line indicates the events with more than three.

In order to try to gain some further insight into the absorption reaction mechanism, in Fig. 6 we show the momentum distributions of protons from the (π^+, ppp) reaction detected at various forward angles. These distributions are similar to those previously reported by Bruckner et al. [4] , who interpreted the bumps in their spectra as being due to the two-step process of quasi-elastic πp scattering followed by two-nucleon absorption. In fact, the search for such bumps was the primary motivation for E722. The dotted line in the first column of Fig. 6 represents the results of the previously-mentioned phase-space model for the $\pi^+\ {}^{12}C \rightarrow pppn{}^8Be$ reaction, weighted so that the residual ^{8}Be nucleus is a spectator carrying only Fermi momentum. The dotted line in the second column of Fig. 6 represents the results of a phase-space model for the two step process $\pi^+\ {}^{12}C \rightarrow \pi^+p\ {}^{11}B \rightarrow ppp{}^9Be$, weighted so that the residual ^{11}B and ^{9}Be nuclei are both spectators carrying only Fermi momentum. The dashed line in the second column represents the sum of the two model calculations. It clearly provides a very good description of the data. We note that evidence

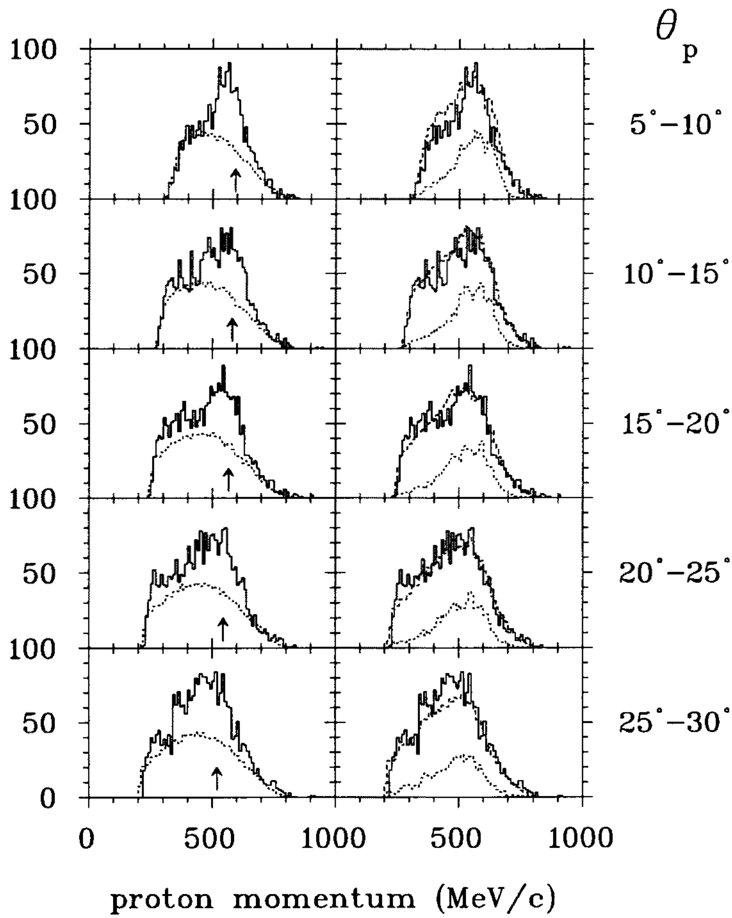

Fig. 6. In both columns, the solid line represents the measured momentum distributions of protons from the $^{12}C(\pi^+, ppp)$ reaction at $T_\pi = 280$ MeV, detected at various forward angles. In the first column, the dotted line represents the result of a model calculation simulating pion absorption on four nucleons. In the second column, the dotted line shows the results of a model calculation simulating the two-step process of πp quasi-elastic scattering followed by two-nucleon absorption, and the dashed line is the sum of the two model calculations.

for pion initial state interactions in multi-nucleon pion absorption has also been recently observed by the LADS collaboration at PSI. We note further that in our data, the bump in the momentum distributions is associated only with those (π^+, ppp) events with high TSUM. The momentum distributions for events with TSUM < 320 MeV, for example, show no structure at all, and are well described by the phase-space model for four-nucleon absorption alone. The implication is that when p_{missing} indicates that only three nucleons participated in the absorption, the mechanism responsible is the two-step one. Addition of distributions obtained from a phase-space model for three-nucleon absorption did nothing to improve the description of the data. Although this does not necessarily exclude a contribution from a direct three-nucleon absorption process, it does appear that any such contribution would have to be quite small.

In order to obtain the total cross sections for the multi-nucleon absorption processes, we have to estimate what fraction of events have fallen within the CHAOS acceptance, and these estimates will be model-dependent. Using the two models mentioned in the previous paragraph, the results of which were illustrated in Fig. 6, we get $\sigma = 2.8$ mb for the two-step process, and $\sigma = 34$ mb for four-nucleon absorption, at $T_\pi = 280$ MeV. A very preliminary analysis indicates that the cross sections for these processes are 3.4 mb and 29 mb at $T_\pi = 240$ MeV, and 3.6 mb and 32 mb at $T_\pi = 200$ MeV. Using the same models, and our normalized (π^+, ppp) data, we can estimate how many of our observed (π^+, pp) events, which we attributed to multi-nucleon absorption on the basis of their large missing momentum (i.e. the events under the long-dashed curve in Fig. 2), can be accounted for. The answer is: all of them. This is surprising, because it implies the cross sections for processes such as (π^+, ppn) and $(\pi^+, ppnn)$ are much smaller than the ones we have been considering up till now. Of course, we cannot make any statement about the importance of the (π^+, pnn) and $(\pi^+, pnnn)$ reactions.

In summary, within the context of the models used in our analysis, it appears that between $200 < T_\pi < 280$ MeV pion absorption sometimes proceeds via the elementary two-body $\pi^+ pn \to pp$ reaction, which is itself sometimes preceeded by quasi-elastic πp scattering of the pion, but mostly via the $\pi^+ ppnn \to pppn$ reaction.

As a final remark, we note that the distribution of the summed kinetic energy of the two protons from our measured $(\pi^+, \pi^+ pp)$ and $(\pi^+, \pi^- pp)$ events agrees very well with the shape attributed to two-nucleon knockout in Fig. 2. Using a three-body phase-space model (which actually does not do a very good job in reproducing any of the measured $(\pi^+, \pi^+ pp)$ distributions, except maybe for the shape of the missing momentum under restrictive TSUM cuts) to estimate acceptances, preliminary estimates for the total cross sections for these two reactions at $T_\pi = 280$ MeV are 20 mb and 3 mb respectively. The sum of these two processes does not explain all of the events under the relevant curve in Fig. 2, leaving room for a sizable $(\pi^+, \pi^0 pp)$ cross section. More definitive statements will have to await analysis of the second part of our data set.

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