In summary, the $^{13}C(\vec{p},\pi^{\pm})$ measurements have provided rich spectra, spectroscopic applications, and a number of striking features and puzzles associated with the relevance of free NN→NNπ results to pion production in the nuclear medium.

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ENERGY DEPENDENCE OF THE (p,π^-) REACTION VERY CLOSE TO THRESHOLD

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Interest in the study of particle production near the reaction threshold stems from the fact that the outgoing channel is dominated by only a few partial waves, and hence may be particularly amenable to a study of its simple general features.[1] For π^+ and π^- produced in proton-nucleus collisions, one expects a quite different qualitative behavior in the region very near threshold. Production of π^+ is "suppressed" by a repulsive Coulomb potential, so that its cross section excitation function rises slowly from threshold. Conversely, π^- production is associated with an attractive Coulomb potential, producing bound pionic-atom states of increasing level density just below threshold, and therefore exhibiting what appears to be a step increase at the point of free pion production.[1-3]

An initial investigation of the energy dependence of the (p,π^+) reaction on several 1p-shell targets[4] near threshold showed the total cross section to scale in energy as phase space times a Coulomb penetrability factor. More recent and refined (p,π^+) studies[5] (at slightly higher bombarding energies), employing simple spin systems which allow a full partial wave analysis, have confirmed the early observations and shown that Coulombic (barrier penetration) and phase space effects dominate the energy dependence of the near threshold (p,π^+) cross sections and analyzing powers. The assumed energy-independence of the strong interaction component of the production process, is consistent with most, but not all, features of these (p,π^+) measurements; the most notable deviations appear in the s-wave (π-nucleus) amplitudes for the two different

transitions studied.[5] It has been shown recently that the (p,π^-) reaction, viewed in the context of a two-nucleon production model, is inherently easier to understand than (p,π^+) because of the highly restrictive processes (reaction path, angular momentum coupling, etc.) by which the (p,π^-) reaction must proceed.[6-8] It was the aim of the present investigation to make the first studies of the energy dependence of the (p,π^-) reaction in a region close to threshold ($8 \leq E_\pi \leq 20$ MeV) for a few selected targets. The $^{13}C(p,\pi^-)^{14}C$ ground state transition has the simple spin form $1/2 + 1/2 \rightarrow 0 + 0$, for which the complete partial wave analysis mentioned above is again possible.[5] The cross section and analyzing power angular distribution data from the present experiment, acquired at bombarding energies of 157 and 171 MeV, were taken to complement similar existing data at the higher bombarding energies of 183 and 190 MeV[5] (as well as cross section distribution data available at 183 MeV[9] and 200 MeV[10]). A global partial wave analysis of the data was performed in order to constrain the energy dependence of the low (mainly s and p) partial wave amplitudes contributing to the production cross section near threshold. Recent studies of the (p,π°) reaction[11] very close to threshold have indicated (albeit in a somewhat model-dependent way) that a significant p-wave contribution is already present at pion energies on the order of 1 MeV above threshold, where one might expect the s wave to clearly dominate.

The present near threshold measurements required significant reconfiguration of the QQSP pion spectrometer focal plane detection system. Vacuum and drift chamber gas windows were reduced in thickness (or eliminated in the case of duplication) in order to minimize the detectable energy for the exiting pions. Even so, pions for the lowest bombarding energy run were stopped and deposited little energy in the thin wedge-shaped plastic timing scintillator placed behind the position-sensing (VDC) drift chamber. Additional scintillators, normally included in the focal plane setup for time-of-flight and energy cuts were of no use here. Hence, the most powerful background reducing cut normally used in off-line analysis of pion production data, namely RF time versus focal plane flight time, could not be used. In its place, angle (inferred from the VDC drift chamber) versus RF time and wedge scintillator energy cuts were found to be adequate in this application.

Angular distributions of the cross section and analyzing power included in the present analysis are presented in Fig. 1. The curves displayed are the result of global fits to all the data at the four bombarding energies. The fitting was performed using a partial wave analysis procedure set within an R-matrix formalism. The formalism employed only a single channel and implicitly assumed no energy dependence of the strong-interaction contributions (see Ref. 5 for details). The resulting energy dependence for the cross section is then given in terms of simple Coulomb barrier penetration and phase space factors. The global fit was obtained by varying the nine parameters associated with the inclusion of s, p, and d wave amplitudes in the analysis. The one arbitrary phase which exists for any set of quantum mechanical amplitudes was in this case chosen to be the s-wave phase whose bare R-matrix value was taken to be zero. Global fits to the entire data set were first performed in order to select the amplitudes and phases giving the observed energy dependence in the reaction. Local fits were then obtained for the cross section and analyzing power angular distributions, using the results

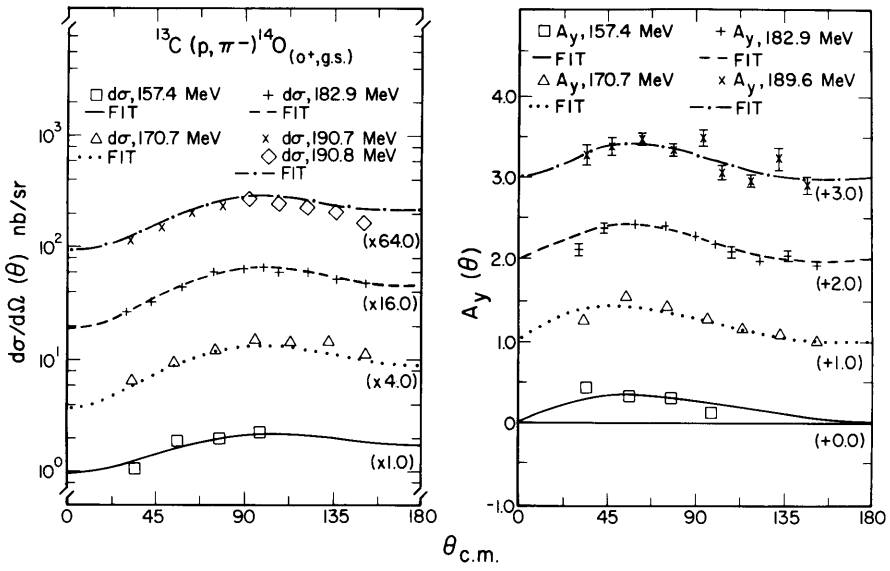

Figure 1. Cross section (left hand panel) and anlayzing power (right hand panel) angular distributions for the $^{13}C(p,\pi^-)^{14}O$ ground state reaction at 157 and 171 MeV from the present experiment along with previously measured[5] results at 183 and 191 MeV. The curves are global partial wave fits to the data as described in the text.

predicted from the global analysis as a starting parameter set. We see that the overall quality of the global fit (curves displayed in Fig. 1) for the four sets of distributions is in general quite good. Results for the local fits, as expected, showed significant improvement in some cases. Because of the lack of a sufficient number of data points for the lowest bombarding energy (due to difficulties in measuring the very low energy pions at the backward spectrometer angles), the entire d-wave and at least one of the p wave amplitudes and phases had to be fixed at their globally predicted values for investigations of the local fit.

The amplitudes and phases obtained from these analyses are shown in Fig. 2, plotted as a function of $\eta = p_\pi/m_\pi$. Parameters are labeled by the exiting pion orbital angular momentum with sub-indices giving the incident channel spin and its projection. The individual points displayed for each parameter are the results from local analyses, with an error bar corresponding to the parameter excursion required to cause a unit change in the customary fitting parameter χ^2, while all other free parameters were allowed to vary. The triplets of curves are the globally fitted results (center curve) with their associated error bands (the higher and lower curves) determined in an analogous way. In general, the smooth variation of parameters given by the global fit is in good agreement with the results of the local analyses. A striking exception is the channel spin = 0 p-wave result at 171 MeV, which disagrees with the globally determined trend (both in amplitude and phase) by about 3 standard deviations. We presently have no explanation for this anomolous behavior, although the 171-MeV data appear to have a small normalization discrepancy in the global analysis depicted in Fig. 1. On the other hand, s-wave

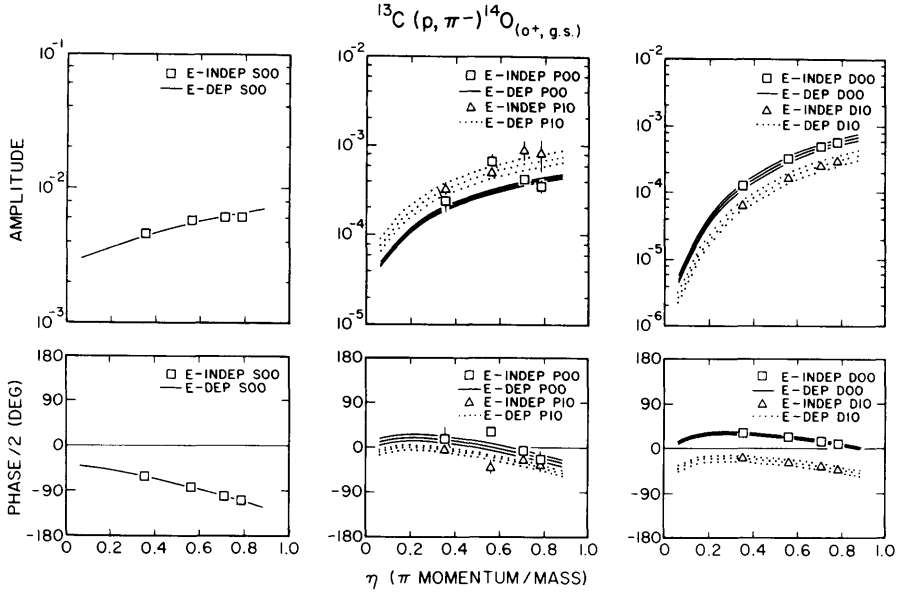

Figure 2. Energy dependence of the amplitudes and phases resulting from both local and global partial wave analyses of the $^{13}C(p,\pi^-)^{14}O$ ground state reaction distributions as described in the text.

discrepancies similar to those observed in the (p,π^+) partial wave study are not observed here. In the present study, both p and d waves contribute most significantly at the higher bombarding energies, as expected, but with a relative strength compared to the s wave about an order of magnitude less than in the (p,π^+) study.[5] The d-wave contribution falls off quite sharply as one approaches the threshold region, while the p-wave contribution retains its diminished significance well into the near-threshold region.

Total cross sections, obtained from Legendre polynomial or partial wave fits of the experimental cross section angular distributionsat each energy, are plotted in Fig. 3 along with the predicted energy dependence of the total cross section obtained from the global partial wave analysis. As expected, the latter gives the proper energy dependence at the four energies involved in the analysis and the nearby data point from Uppsala.[9] However, it also correctly extrapolates to the integrated cross section distribution measurement of Hoistad et al.,[10] obtained at somewhat higher bombarding energies. In summary, there is no need to introduce an explicit energy-dependence in the strong-interaction amplitudes for pion production in order to understand the $^{13}C(p,\pi^-)^{14}O$ results treated here.

This determination of the energy dependence of the partial waves for low outgoing pion energies also allows an extrapolation of the total cross section right down to threshold. Such an extrapolation, as given by the formalism used in the present analysis is shown in Fig. 3 by the solid curve extending to small values of η. However, we know that very close to threshold, the curve is expected to flatten out and approach a constant value.[12] For s-waves which must ultimately dominate, this is the result of the linear

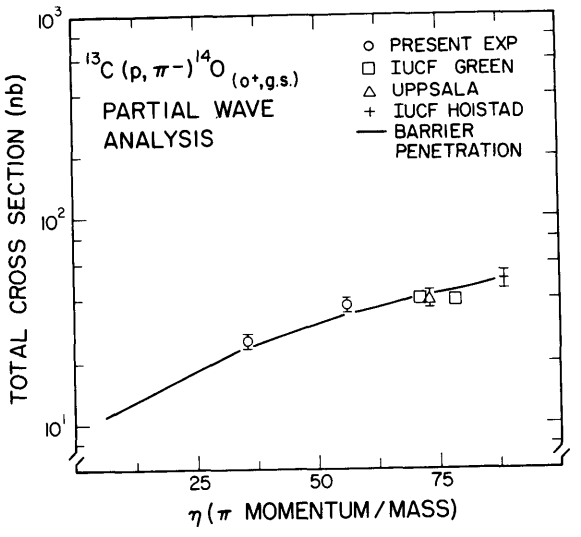

Figure 3. Energy dependence of the total cross section for the $^{13}C(p,\pi^-)^{14}O$ ground state reaction plotted as a function of $\eta = p_\pi/m_\pi$. Points derived from the present measurements at 157 and 171 MeV, and previous measurements at 183 and 191 MeV,[5] 185 Mev,[9] and 200 MeV[10] are plotted. The curve is a result of a global partial wave analysis of the 157, 171, 183, and 190-MeV data sets extrapolated in energy as described in the text.

phase space dependence on pion momentum cancelling the inverse dependence on momentum from the standard Gamow factor in the Coulomb penetrability. Hence, a reasonable estimate of the free pion production cross section at threshold from the extrapolation presented in Fig. 3 would be about 10 nb. Since the foregoing analysis was carried out in a R-matrix formalism, the Coulomb wave functions are properly normalized at the "inner region" radius and hence no additional finite nucleus correction factor[2,12] need be applied.

From continuity arguments, the energy averaged cross section for production of subthreshold pionic atom ns bound states with high principal quantum numbers n must approach the same limit as the cross section for outgoing pions produced at or just above threshold.[2,3] Hence, the free pion production cross section at threshold may be related[3] to the branching ratio for decay, by single proton emission, of pionic atom ns states, and ultimately to decay of the 1s state. Such branching ratios are known from pionic atom studies on a variety of light targets,[13] although not for the final nucleus (^{14}O) in question here. With an assumed target independence of π^- absorption ground state branching ratios, and an estimate of equal contributions from both ground and excited nuclear states to measured proton yields from π^- absorption on ^{12}C and ^{14}N, an estimate[3] of 25 nb was made for the $^{13}C(p,\pi^-)^{14}O$ ground state total free pion production cross section at threshold. This appears to be inconsistent with the estimate of 10 nb from the present work, implying that we might selectively question assumptions made in either the pionic atom or partial wave extrapolation analyses. Certainly, detailed systematic studies of the π^- absorption channels in 1p-shell nuclei would be extremely helpful and timely. One possible explanation is, for example, that the proton yields for π^- ground state absorption are a factor of 2-3 smaller for proton rich targets (e.g., ^{14}O) than for targets with N=Z.

As a final note, a study of the behavior close to threshold of the very strongly and selectively excited high-spin states which have been observed[7] in (p,π^-) would be complementary to study of the low-spin (and weakly excited from momentum matching considerations) ^{13}C ground state transition reported here. However, the former is no longer a simple spin system amenable to the present partial wave analysis, so that experimental techniques must push the cross section determination closer toward threshold. We expect that the behavior of both types of states in the very near

threshold region may have important implications for the further understanding of the pion production mechanism as well as future connections to studies in the field of pionic atoms. In the latter regard, from a purely experimental point of view, an understanding of the systematics of (p,π^-) cross sections at (or near) threshold is important for the design of possible future IUCF Cooler Ring experiments, wherein pionic atoms could be created and studied "from the inside out".[3,14]

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WHERE IS THE HIGH-SPIN STRENGTH IN HEAVY TARGET (p,π^-) REACTIONS?

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An unexpected, selective concentration of discrete high spin reaction strength (E_x = 3-6 MeV) has been shown[1] to be a systematic feature of (p,π^-) spectra obtained from many target nuclei ranging from the 1p shell up to the region A ≃ 90. The strongly excited states were interpreted[1,2] to have a 2 particle (protons) -1 hole (neutron) configuration with respect to the target nucleus ground state, coupled to maximal (stretched), or near maximal spin, in order to accommodate the large linear and angular momentum mismatch inherent to the (p,π) reaction. The selective population of these states is favored by the assumed dominance[3] in the reaction mechanism of the fundamental and unique two-nucleon process $p + n \rightarrow p + p + \pi^-$, where the incident proton interacts with a target neutron from a specific shell model orbital. The resulting spectrum of discrete 2p-1h configuration states is largely determined by the number of available