# EVIDENCE FOR TWO-NUCLEON PROCESSES IN A(p,$\pi^-$)A+1

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In the currently favored (so-called "two-nucleon") models of (p,$\pi$) reactions,[1,2] the production mechanism involves the explicit interaction of the incident nucleon with a target nucleon. This mechanism (as opposed to single particle "pionic stripping") facilitates sharing of the large momentum transfer in the residual nucleus. While there have been no conclusive experimental tests of such models, the literature does contain hints that two-nucleon (N-N) processes play a significant role in nuclear pion production. For example, similarities with experimental results for the fundamental $p+p \to d+\pi^+$ process have been observed for at least some (p,$\pi^+$) transitions on nuclei both in the near-threshold energy dependence of the total cross section[3] and in the analyzing power (see ref. 4, but also refs. 5 and 6 for counterexamples). On the other hand, studies of inclusive $\pi^+$ and $\pi^-$ absorption processes on nuclei have been presented as evidence of an important role for mechanisms involving considerably more than two active nucleons,[7] although the same data have been alternatively interpreted in a simple two-nucleon volume absorption model.[8]

In the present work we have sought to identify possible signatures of two-nucleon production processes which might be exhibited in selected (p,$\pi$) transitions to discrete nuclear final states. The possible free N-N charged pion production processes are:

a) $p + p \to d + \pi^+$

b) $p + p \to p + n + \pi^+$

c) $p + n \to n + n + \pi^+$

d) $p + n \to p + p + \pi^-$ .

We note that, in contrast to the general situation for (p,$\pi^+$) reactions, only a single two-nucleon process i.e. d), involving interaction with a target neutron, can contribute to (p,$\pi^-$). When the configurations of the initial and final [2p(protons)-1h(neutron)] states are known, the shell-model orbital of the struck target neutron is uniquely determined. If N-N processes do indeed play a dominant role in nuclear pion production, the above restrictions may serve to make (p,$\pi^-$) reactions simpler to understand than (p,$\pi^+$). In particular, they have led us to predict, on general grounds, a systematic difference in near-threshold ($\vec{p}$,$\pi^-$) analyzing powers between transitions involving target neutrons from $j_> = \ell+1/2$ vs. $j_< = \ell-1/2$ orbitals, and, under more stringent assumptions, a simple scaling of the (p,$\pi^-$) cross section across an isotopic series of targets. Neither of these features would be expected to apply in general for (p,$\pi^-$) mechanisms involving more than two nucleons, nor for (p,$\pi^+$) even in a pure two-nucleon model. These predictions are discussed below and compared with measurements for the $^{12,13,14}$C(p,$\pi^-$)$^{13,14,15}$O$_{g.s.}$ transitions.

The measurements were performed using the polarized proton beam from IUCF and the new QQSP pion spectrometer.[9] Cross sections $\sigma(\theta)$ and analyzing powers $A_y(\theta)$ were measured at 8-10 angles in the range $31° < \theta_{cm} < 153°$ for $^{12}$C(p,$\pi^-$)$^{13}$O, $^{13}$C(p,$\pi^-$)$^{14}$O, and $^{14}$C(p,$\pi^-$)$^{15}$O, at $E_p$ = 205, 190, and 183 MeV, respectively. These bombarding energies were chosen to produce the same nominal center-of-mass pion energy (40 MeV) for the ground state (g.s.) transition in each case, in order to minimize differences arising from changes in pion distortions. The thicknesses (48-98 mg/cm$^2$) of the natural $^{12}C$ and enriched (95%) $^{13}C$ targets were determined to ±10% uncertainty by weighing. The $^{14}C$ target had an enrichment of only 67%, and relative isotopic abundances were determined by comparing 200 MeV proton elastic scattering data with previously measured $^{12,13}C(p,p)$ cross sections.[10] Systematics of the $^{12,13,14}C$ elastic scattering distributions as a function of momentum transfer were used to infer the $^{14}C$ thickness of 20 mg/cm$^2$ (70 mC) to an estimated uncertainty of ±15%. The results for $\sigma(\theta)$ and $A_y(\theta)$ are plotted in Fig. 1, with error bars reflecting statistical uncertainties only. The absolute normalization error for the $\sigma(\theta)$ data is dominated by the above-mentioned target thickness uncertainties.

Our expectations for $\sigma(\theta)$ and $A_y(\theta)$ are most readily understood in the context of a simple shell model picture for $^{12,13,14}C$ and $^{13,14,15}O$. For example, a $(p,\pi^-)$ transition between the dominant ground-state configurations in $^{13}C(1/2^-)$ and $^{14}O(0^+)$ [or between $^{14}C(0^+)$ and $^{15}O(1/2^-)$] can be mediated by the two-nucleon process d) above only if the incident proton interacts with a $p_{1/2}$ target neutron. (Note that as the two final-state $p_{1/2}$ protons produced are coupled to spin zero, $\Delta j$ is equal to the total j of the struck neutron.) In contrast, the $\Delta j$ = 3/2 transition between $^{12}C$ and $^{13}O$ would involve a $p_{3/2}$ target neutron. While N-N processes involving target neutrons from other subshells are conceivable, they would join configurations which are only weakly admixed in the states of interest.[11]

It is seen in Fig. 1a that there is a particularly striking difference between the $(p,\pi^-)$ analyzing powers measured for the $\Delta j$ = 3/2 transition and the $\Delta j$ = 1/2 transitions, with $A_y(\theta)$ in the forward hemisphere being large and negative for the former and positive for the latter transitions. Previous results[12] for another $\Delta j$ = 3/2 p-shell case, $^9Be(p,\pi^-)^{10}C_{g.s.}$, also show a negative $A_y(\theta)$ at forward angles. A clear j-dependent

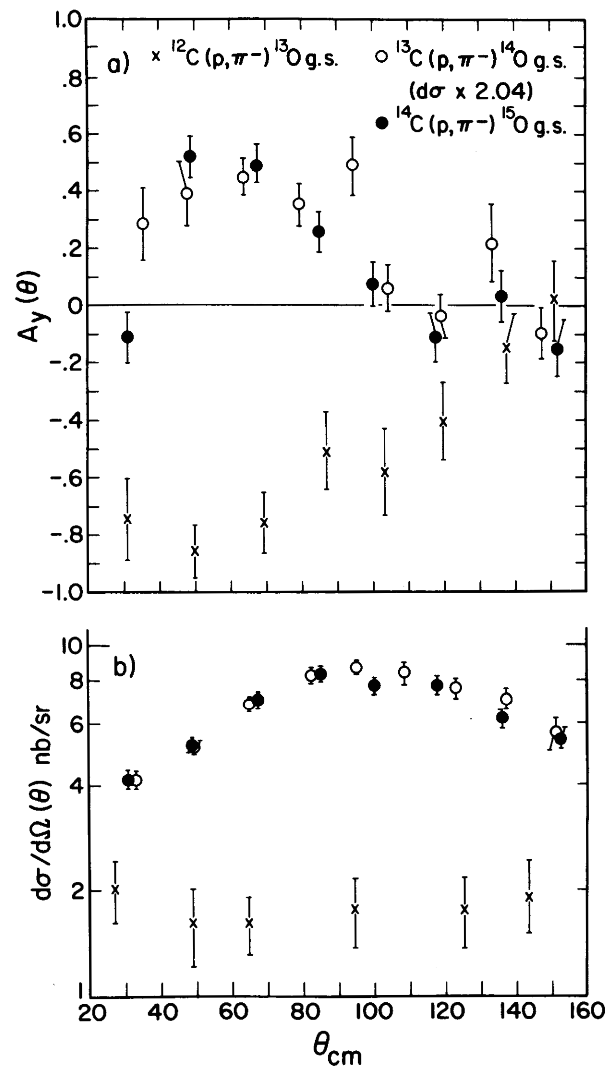


Figure 1. Cross section and analyzing power angular distributions for $^{12}C(p,\pi^-)^{13}O_{g.s.}(\Delta j=3/2^-)$, $^{13}C(p,\pi^-)^{14}O_{g.s.}(\Delta j=1/2^-)$ and $^{14}C(p,\pi^-)^{15}O_{g.s.}(\Delta j=1/2^-)$. Cross section data for $^{12}C$, from Ref. 13, are for $E_p$ = 200 MeV.

difference in $A_y(\theta)$ is in fact expected from N-N process d) on the following general semi-classical grounds. For nuclear final states where the two residual protons are coupled to spin zero, angular momentum and parity conservation require 1) the interacting proton and neutron in the $p + n \rightarrow (pp)_0 + \pi^-$ process to be in a relative spin triplet state, and 2) the struck neutron to be in a state of uniquely defined spin and parity within the target nucleus. In addition, (see Fig. 2), near-threshold pion production (below threshold for the free N-N process) requires the Fermi motion of the struck nucleon to be directed predominantly toward the incident nucleon. As a result of these conditions, $j_>$ target neutrons will interact preferentially with spin-up incident protons on one "side" of the nucleus and with spin-down protons on the other, with the preferred sides reversed for $j_<$ neutrons. Distortions generally introduce a further "sidedness" to nuclear rections: e.g., they will likely cause a preference for the $\pi^-$ to emerge on the same side of the nucleus as the projectile (as in Fig. 2) or, alternatively, on the opposite side (as suggested by the measured $A_y(\theta)$ in Fig. 1a). The combination of these arguments leads to a prediction of a systematic sign difference in $A_y(\theta)$ for $(p,\pi^-)$ transitions involving $j_>$ and $j_<$ target neutrons. This j-dependent effect should be superimposed on a common contribution to $A_y(\theta)$ arising from the fundamental process $\vec{p} + n \rightarrow (pp)_0 + \pi^-$ itself. No such j-dependence would be expected for $(p,\pi^+)$, where conditions 1) and 2) (above) are not satisfied, and the spin system of the interacting nucleons is far less constrained.

The predictions for the behavior of $A_y(\theta)$ follow almost directly from an assumed dominant role of the fundamental N-N processes, and hence the $(p,\pi^-)$ data in

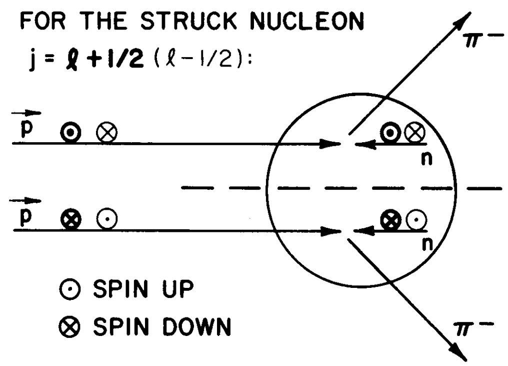


Figure 2. Schematic illustration of the expected j-dependence in near-threshold $(p,\pi^-)$ analyzing powers, viewed in a two-nucleon picture. Spin up (down) protons interact primarily with spin up (down) neutrons, thereby producing pions preferentially on different sides of the nucleus. This results in a sign difference in $A_y(\Theta)$ for struck neutrons with $j = \ell \pm 1/2$.

Fig. 1a appear to support the validity of this assumption. It should be noted, however, that data for $^{14}C(p,\pi^-)^{15}O^*(6.2\ MeV, 3/2^-)$ also collected during the present set of measurements do not fit in with the above systematics for the ground state transitions, suggesting a significantly different reaction mechanism for this excited state transition.

Turning now to the $\sigma(\theta)$ data in Fig. 1b, we note that for $^{13,14}C(p,\pi^-)$, which both involve interaction with neutrons from the same orbital ($p_{1/2}$), the $\sigma(\theta)$ [and $A_y(\theta)$] distributions are expectedly very similar, whereas the $^{12}C(p,\pi^-)$ distribution ($p_{3/2}$ neutron) has a different character. The observed (angle-independent) ratio of absolute cross sections for $^{13,14}C(p,\pi^-)$ may also be understood from simple considerations of N-N processes, without more detailed knowledge of the production mechanism, provided we ignore energy differences among, and invoke closure over, the intermediate states reached for the two targets. Then we should expect a simple scaling of $\sigma(\theta)$ with occupancy of the relevant neutron subshell ($p_{1/2}$), i.e., by a factor of two in the simplest shell model picture.[14] Better estimates of $p_{1/2}$ neutron occupancy based on theoretical 1p-shell wave functions,[11] modify the expected ratio only slightly (to 2.04). The excellent agreement of $2.04 \times \sigma^{13}(\theta)$ with $\sigma^{14}(\theta)$ for the $^{13,14}C(p,\pi^-)$ distributions, well within uncertainties over the full angular range (Fig. 1b), supports the simple scaling picture and validates the assumptions leading to this predicted N-N process signature.

In summary, interpretation of the experimental evidence obtained supports the dominant role of two-nucleon processes in $(p,\pi)$ near threshold. In particular, the similarity in shape of $\sigma(\theta)$ and $A_y(\theta)$ data for $^{13,14}C(\vec{p},\pi^-)$, and the prediction, borne out by the $^{12,13,14}C(\vec{p},\pi^-)$ data, of a j-dependence for $(\vec{p},\pi^-)$ analyzing powers, follow directly and generally from an assumed dominance of fundamental $NN \rightarrow NN\pi$ processes for pion production in the nuclear environment. The observed scaling of the $^{13,14}C(p,\pi^-)$ cross sections, although more sensitive in principle to the detailed nature of the two-nucleon mechanism involved, agrees well with the result expected in the simplest shell model picture. Clearly, data of this type will be of use in constraining future calculations within the framework of the two-nucleon model.[2] Further measurements for selected $(\vec{p},\pi^-)$ transitions are needed to determine if the systematics based on these initial cases will persist.

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