# $^{12,13}C(p_{pol},\pi^{\pm})$ Reactions and Quasifree $N_{pol}N \to NN\pi$ Expectations

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The analyzing-power behavior and the isospin dependence of the cross sections for reactions $^{13}C(p_{pol},\pi^{\pm})$ and $^{12}C(p_{pol},\pi^{+})$ near threshold are compared with expectations from pion-production measurements in *free* two-nucleon collisions. The general agreement for $(p_{pol},\pi^{+})$ suggests that the stable analyzing-power pattern observed for $(p_{pol},\pi^{-})$ continuum transitions may reflect the as yet unmeasured free $p_{pol}n \to pp\pi^{-}$ behavior. We also discuss constraints imposed by quasifree $N_{pol}N \to NN\pi$ expectations on the interpretation of anomalous $(p_{pol},\pi^{+})$ results for two strongly populated states at high excitation in $^{13,14}C$.

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Considerable evidence has accumulated in recent years that reactions $A(p,\pi)A+1$ on nuclei are dominated by a two-nucleon mechanism (TNM), i.e., by $NN \to NN\pi$ processes occurring within the nuclear medium.[1-6] Particularly strong indications come from studies of the $(p_{pol},\pi^{-})$ reaction near threshold,[2-6] where the TNM is able to explain, at least qualitatively, the pronounced selectivity observed for discrete high-spin two-particle, one-hole (2p-1h) states,[3,4] the shape and target dependence of the continuum,[5] and even some cross-section and analyzing-power features for selected weak transitions.[2] While the arguments made in Refs. 2-6 depend on the explicit participation of two nucleons (one from the target nucleus), they do not require treatment of the pion production as a *quasifree* $NN \to NN\pi$ process. Indeed, one might expect *a priori* quite different off-shell behavior for pion production in a free two-nucleon collision versus one occurring inside a nucleus.[7] In this light, $(p_{pol},\pi^{+})$ results obtained for several light nuclei have suggested a surprisingly strong similarity in analyzing-power behavior to the free $p_{pol}p \to d\pi^{+}$ reaction.[1] A more detailed investigation of nuclear medium effects on the fundamental $NN \to NN\pi$ amplitudes can provide important input to our understanding of pion interactions in nuclei.

In the present work, we report some results of a study of $(p_{pol},\pi^{\pm})$ reactions on $^{12,13}C$ targets, bearing on the comparison to two particular aspects of free $NN \to NN\pi$ processes: the analyzing-power behavior and the isospin dependence of the amplitudes. Analyzing-power $(A_y)$ measurements at bombarding energies below 450 MeV for $p_{pol}p \to d\pi^{+}$ (in the work of Jones[8] and $p_{pol}p \to np\pi^{+}$ (in the work of Falk *et al.*[9]) show that $A_y$ is typically large and negative over most of the angle range,[8] with relatively little difference between the two-body and three-body final states.[9] Phase-shift analyses of free $NN \to NN\pi$ data[10]—involving an isospin decomposition of the cross sections $\sigma_{TT'}$ in terms of the total isospin of the initial $(T)$ and final $(T')$ nucleon pairs—reveal that within $\sim 150$ MeV of threshold $\sigma_{10}$ is an order of magnitude stronger than $\sigma_{11}$, which in turn seems much stronger than $\sigma_{01}$. Consequently, the cross section for $pp \to (np)_{T'=0}\pi^{+}$ exceeds by a factor $\sim 10$ that for $pn \to nn\pi^{+}$ and $pn \to pp\pi^{-}$, the latter being the only two-nucleon process contributing to $(p,\pi^{-})$ reactions on nuclei. A similar ratio has been deduced[11] from studies of $\pi^{\pm}$ absorption on $s$-wave nucleon pairs in $^{3}He$ at $T_{\pi} \le 100$ MeV.

The $^{13}C(p_{pol},\pi^{\pm})$ and $^{12}C(p_{pol},\pi^{+})$ measurements were made with the $T_p = 200$ MeV polarized proton beam at the Indiana University Cyclotron Facility. This energy is well below the laboratory threshold for $NN \to NN\pi$ on a stationary nucleon; however, as viewed from the rest frame of target nucleons with momenta up to the Fermi momentum, the equivalent bombarding energy spans a range up to 150 MeV above threshold in the $NN$ system. The emerging pions were detected with a magnetic spectrometer, by use of techniques described in detail elsewhere.[6]

Since the reactions $^{13}C(p,\pi^{\pm})$ populate mirror nuclei,

 

$^{14}$C and $^{14}$O, their comparison permits study of the different underlying $NN \rightarrow NN\pi$ isospin channels inside a nucleus under similar nuclear-structure and distortion conditions. Forward-angle spectra obtained for the two reactions are compared in Fig. 1. The absolute cross-section scale in Fig. 1 is an order of magnitude greater for $(p,\pi^+)$ than for $(p,\pi^-)$, suggesting an overall similarity in isospin-dependence $(\sigma_{10}/\sigma_{11})$ to the free $NN \rightarrow NN\pi$ processes. The *relative* strengths of different states also differ appreciably between the two reactions, but in ways generally consistent with TNM expectations.[3] For example, low-spin states with relatively poor momentum matching are populated more strongly in $(p,\pi^+)$, where amplitudes involving struck and final-state nucleons in various shell-model orbitals can often add coherently. In contrast, *all* $(p,\pi^-)$ transitions are effected by quite restricted TNM paths ($pn \rightarrow pp\pi^-$ on a target neutron from an orbital specific to the initial- and 2p-1h final-state configurations), yielding a relative population of states dominated by momentum-matching considerations.[3] The resulting implication that mirror states populated strongly in both reactions correspond to high-spin 2p-1h transitions facilitates spectroscopic applications (e.g., a $5^-$ assignment to the strong states near $E_x = 15$ MeV in $^{14}$O and $^{14}$C) to be discussed in a future in-depth report on these data. We concentrate below on results for continuum regions of the $^{13}$C$(p,\pi^\pm)$ spectra, and for the discrete transition to the strong, sharp, previously unknown state at $E_x = 23.2$ MeV in $^{14}$C. The $^{12}$C$(p_{\text{pol}},\pi^+)$ data, acquired to complement results for the latter transition, show (Fig. 1) a strong state at comparable $E_x$ (21.4 MeV) in $^{13}$C.

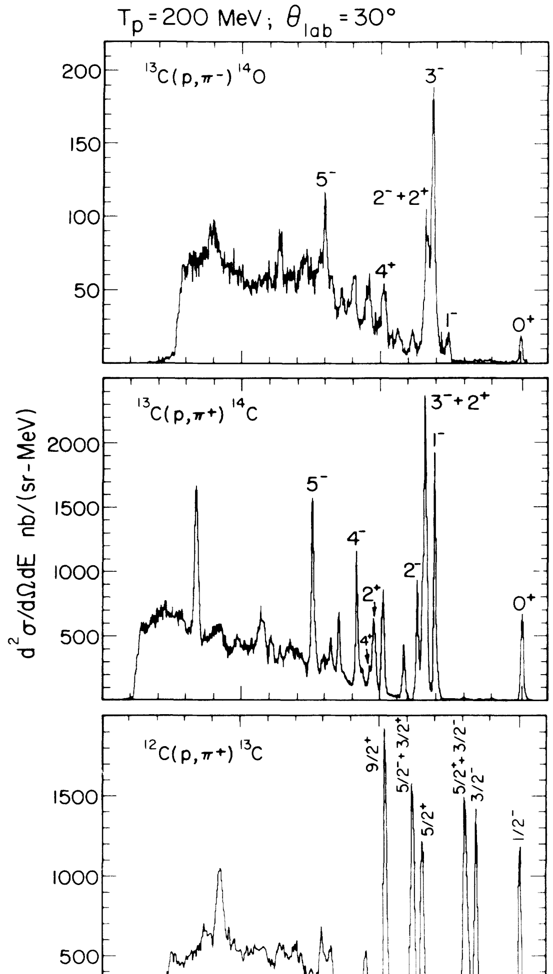


FIG. 1. Comparison of forward-angle spectra for the $^{13}$C$(p,\pi^\pm)$ and $^{12}$C$(p,\pi^+)$ reactions. Spin and parity assignments established by previous work or suggested by the $(p,\pi)$ results are indicated for a number of states.

The most striking feature of the $(p_{\text{pol}},\pi^+)$ results is the great similarity of the overall analyzing-power $(A_y)$ behavior to that of the *free* $\sigma_{10}$ channels. This is illustrated in Fig. 2 by a comparison of our $A_y(\theta)$ measurements for two typical continuum bins of the $^{13}$C$(p_{\text{pol}},\pi^+)$ spectrum with free $p_{\text{pol}}p \rightarrow d\pi^+$ results[8] transformed to the nucleon-nucleus frame. The transformation assumes the struck target proton to move toward the beam with momentum appropriate to yield the observed pion four-momentum in a two-body collision. The corresponding free-$A_y$ value is then extracted, by interpolation among existing $p_{\text{pol}}p \rightarrow d\pi^+$ results,[8] at the

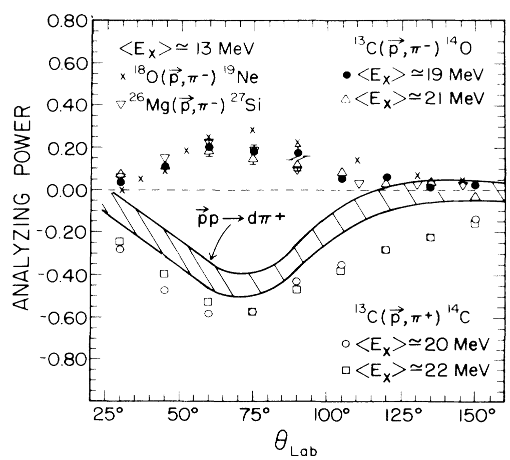


FIG. 2. Measured analyzing powers at $T_p = 200$ MeV for representative 1-MeV-wide regions (centered about the values $\langle E_x \rangle$) of the $^{13}$C$(p,\pi^\pm)$ continua. Shown for comparison are $(p_{\text{pol}},\pi^-)$ continuum $A_y(\theta)$ from Ref. 12 for $^{18}$O and $^{26}$Mg targets. The cross-hatched region represents $A_y(\theta)$ for $p_{\text{pol}}p \rightarrow d\pi^+$, deduced from measurements (Ref. 8) with an interpolation uncertainty indicated by the width of the band, and transformed to the $p$-nucleus frame as described in the text.

bombarding energy and pion angle calculated in the rest frame of the struck proton. The good agreement obtained with the $^{13}C(p_{pol},\pi^+)$ data in Fig. 2 by use of such a simple kinematic transformation (and with effects of nuclear distortions ignored) suggests that pion production in the nucleus can indeed be viewed as a quasifree two-body process (a similar conclusion has been reached also in a recent study at higher energy[13]). It is important to note that very similar $A_y$ distributions are also observed for the rest of the $^{13}C(p_{pol},\pi^+)$ continuum as well as for most transitions to discrete states (not only for $^{13}$C, but for various light-target nuclei; see the work of Auld *et al.*[1] and Sjoreen *et al.*[14] Discrete-state $(p,\pi^+)$ transitions usually involve coherent contributions from a variety of nucleon orbitals.

We observe (and will present in the forthcoming paper mentioned above) a stronger state dependence of $A_y(\theta)$ for $^{13}C(p_{pol},\pi^-)$ transitions (see also examples in Refs. 2 and 6), where the angular-momentum coupling of the struck nucleon within the target nucleus is much more constrained. However, we find (Fig. 2) quite stable $A_y(\theta)$ behavior for *continuum* bins of the $^{13}C(p_{pol},\pi^-)$ spectrum, where averaging over many state-dependent contributions of opposite sign may be expected. Indeed, continuum portions of $(p_{pol},\pi^-)$ spectra for several other target nuclei[6,12] exhibit strikingly similar $A_y(\theta)$, as also shown in Fig. 2. In view of the correspondence obtained for $(p_{pol},\pi^+)$, it is tempting to interpret this stable $A_y$ pattern for the $(p_{pol},\pi^-)$ continuum as a reflection of the intrinsic $p_{pol}n\rightarrow pp\pi^-$ behavior. Unfortunately, no near-threshold measurements for the relevant ($\sigma_{11}$ or the apparently much weaker $\sigma_{01}$) channels exist to confirm this speculation. It is interesting to note, however, that recent theoretical calculations[15] suggest a sign difference between $A_y$ for the $\pi^+$ vs $\pi^-$ production free channels such as we observe in Fig. 2. The predominant signs of $A_y$ seen for the $(p_{pol},\pi^+)$ and $(p_{pol},\pi^-)$ continua may very well simply reflect the different characteristic couplings of relative orbital and spin angular momenta (in initial and final $NN$, as well as intermediate $\Delta N$ states, as listed, for example, in Ref. 8) which should dominate the two different isospin amplitudes near threshold.

The systematic behavior of $(p_{pol},\pi^+)$ analyzing powers suggests that those few transitions that exhibit anomalous $A_y(\theta)$ may not be dominated by the free $\sigma_{10}$ channels. This is the case, for example, for the transition to the $4^+$ state at $E_x=10.74$ MeV in $^{14}$C, which is believed[16] to have predominantly a $(vsd)^2$ configuration with respect to the $^{12}$C ground state, accessible in a TNM $(p,\pi^+)$ reaction only via the $pn\rightarrow nn\pi^+$ $(T'=1)$ process. The $4^+$ state is, however, very weakly populated (see Fig. 1): Its cross section is comparable to that of typical $(p,\pi^-)$ transitions, as expected from the relative weakness of the free $\sigma_{11}$ channel. The most interesting anomalies occur for the high-lying states at $E_x=23.2$ MeV in $^{14}$C and $E_x=21.4$ MeV in $^{13}$C (see Fig. 1), representing the only *strong* peaks in these $(p,\pi^+)$ spectra which deviate dramatically from the usual $A_y$ behavior. As shown in Fig. 3, both exhibit $A_y(\theta)$ consistent with zero at all angles, as well as quite similar cross-section angular distributions, suggesting similar underlying structure. The $^{14}$C state, unidentified in previous work, appears to be populated weakly in back-angle $^{14}C(e,e')$ spectra,[17] with strength more typical of natural-parity than of unnatural-parity transitions. The $^{13}$C state at 21.4 MeV coincides in $E_x$ with a strong $M4$ transition observed[18,19] in both $(e,e')$ and $(\pi,\pi')$. Shell-model calculations[20] suggest several candidate states for this $M4$ excitation, with $J^\pi=\frac{7}{2}^+$ or $\frac{9}{2}^+$ and $T=\frac{3}{2}$ or $\frac{1}{2}$.

One possible explanation of these anomalous states in $^{13,14}$C that would be at least qualitatively consistent with their excitation energies (compared with expectations from isobaric nuclides), their observed widths, and the above inelastic scattering and shell-model results, is that both are $T_>$ states of moderate angular momentum [e.g., $|{}^{12}C\times(\nu p_{1/2})(p_{3/2})^{-1}(p_{1/2})(d_{5/2})\rangle_{3^-,T=2}$ in $^{14}$C and $|{}^{12}C\times(p_{3/2})^{-1}(p_{1/2})(d_{5/2})\rangle_{7/2^+,T=3/2}$ in $^{13}$C]. Such a state in $^{14}$C would have only a single open isospin-conserving particle-decay channel [to $^{13}B(g.s.)+p+2.4$ MeV], accounting for the sharpness of the observed peak (see Fig. 1). Furthermore, such $T_>$ states could be populated only via $\Delta T=\frac{3}{2}$ $(p,\pi^+)$ transitions, to which the $\sigma_{10}$ isospin channel cannot contribute, providing a natural explanation for anomalous $A_y$ behavior. However, the large $(p,\pi^+)$ cross sections measured for these transitions [comparable to those seen for strong $\Delta T=\frac{1}{2}$ $(p,\pi^+)$ transitions], together with the *absence* in Fig. 1 of a similarly strong mirror $(p,\pi^-)$ excitation,[21] argue against our interpreting the peaks as relatively pure $T_>$ states. On the other hand, a sizable, but not

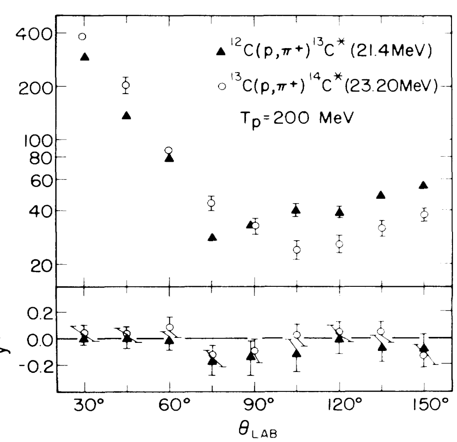


FIG. 3. Cross-section and analyzing-power distributions for the anomalous $(p_{pol},\pi^+)$ transitions to the states at $E_x=21.4$ MeV in $^{13}$C and 23.2 MeV in $^{14}$C.

dominant, $T_<$ admixture would introduce a $\Delta T=\frac{1}{2}$ contribution—and, hence, probably a strong enhancement in the cross section—for the $(p,\pi^+)$, but not for the mirror $(p,\pi^-)$, transition. The analyzing power for such a $(p_{\rm pol},\pi^+)$ transition might well fall in between the negative $(\Delta T=\frac{1}{2})$ and positive $(\Delta T=\frac{3}{2})$ values typifying (see Fig. 2) the coherent contributing amplitudes. Such isospin mixing is in fact suggested by the $^{13}$C$(\pi,\pi')$ data[19] for $E_x=21.4$ MeV.

The mixed-isospin scenario and alternative interpretations for these two anomalous transitions can be tested experimentally. For example, the isospin of the 21.4-MeV state in $^{13}$C may be constrained via $^{12}$C$(p,\pi^+n)$ coincidence measurements of the relative branching ratio for decay to the $1^+$, $T=1$ (15.11 MeV) vs $1^+$, $T=0$ (12.71 MeV) states in $^{12}$C. A possible alternative is to view these states as high-spin $T_<$ states [e.g., $|^{12}\mathrm{C}\times(\pi p_{3/2})^{-1}(\nu d_{5/2})(\pi d_{5/2})\rangle_{13/2^-,T=1/2}$ in $^{13}$C, and the corresponding $7^+$, $T=1$ configuration in $^{14}$C], populated through the $\sigma_{10}$ $NN\rightarrow NN\pi$ channel, and accidentally overlapping in $E_x$ with different states seen in $(e,e')$ and $(\pi,\pi')$. It is known that in $(p_{\rm pol},\pi^-)$ reactions, 2p-1h states such as these, with the maximum possible angular momentum attainable within the valence shells, exhibit systematically different $A_y$ than do lower-spin states[6]—perhaps a similar behavior applies in $(p_{\rm pol},\pi^+)$ as well. Were this the case, we would expect these states also to be populated strongly in appropriate high-$q$ transfer reactions, e.g., $^{11}$B$(\alpha,p)^{14}$C and $^{11}$B$(\alpha,d)^{13}$C, which have not previously been studied to sufficiently high excitation.

In summary, the typical $(p,\pi^+)/(p,\pi^-)$ cross-section ratios and $(p_{\rm pol},\pi^+)$ analyzing powers reported here are consistent with simple near-threshold expectations for a quasifree $NN\rightarrow NN\pi$ process. Polarization measurements for the *free* reaction $p_{\rm pol}n\rightarrow pp\pi^-$ (or $p_{\rm pol}p\rightarrow pp\pi^0$ if we can neglect $\sigma_{01}$) are needed to test whether the stable $(p_{\rm pol},\pi^-)$ continuum analyzing powers observed, with sign opposite to that for $(p_{\rm pol},\pi^+)$, also simply reflect the free $NN\rightarrow NN\pi$ behavior. The results, which are most difficult to fit into a quasifree TNM picture, are those for the strong $(p,\pi^+)$ transitions to states at $E_x=21.4$ MeV in $^{13}$C and 23.2 MeV in $^{14}$C, both with essentially zero analyzing power. Experiments which may elucidate the nature of these particular states have been suggested.

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[1]E. G. Auld *et al.*, Phys. Rev. Lett. **41**, 462 (1978).

[2]W. W. Jacobs *et al.*, Phys. Rev. Lett. **49**, 855 (1982).

[3]S. E. Vigdor *et al.*, Phys. Rev. Lett. **49**, 1314 (1982), and Nucl. Phys. **A396**, 61c (1983).

[4]B. A. Brown *et al.*, Phys. Rev. Lett. **51**, 1952 (1983).

[5]O. Scholten and H. Toki, Phys. Rev. C **34**, 601 (1986).

[6]T. G. Throwe *et al.*, to be published.

[7]L. S. Kisslinger, in *Pion Production and Absorption in Nuclei—1981*, edited by R. D. Bent, AIP Conference Proceedings No. 79 (American Institute of Physics, New York, 1982), p. 233.

[8]G. Jones, Ref. 7, p. 13, and Nucl. Phys. **A416**, 157c (1984).

[9]W. R. Falk *et al.*, Phys. Rev. C **32**, 1972 (1985).

[10]B. J. Verwest and R. A. Arndt, Phys. Rev. C **25**, 1979 (1982).

[11]R. P. Redwine, Nucl. Phys. **A434**, 239c (1985), and references therein.

[12]J. J. Kehayias *et al.*, Phys. Rev. C **33**, 1388 (1986).

[13]W. R. Falk *et al.*, Phys. Rev. C **33**, 988 (1986).

[14]T. P. Sjoreen *et al.*, Phys. Rev. C **24**, 1135 (1981).

[15]Z.-J. Cao and W.-Y.P. Hwang, Phys. Rev. C **34**, 1785 (1986), and private communication.

[16]H. T. Fortune *et al.*, Phys. Rev. Lett. **40**, 1236 (1978).

[17]M. A. Plum *et al.*, Phys. Lett. **137B**, 15 (1984).

[18]R. A. Lindgren, J. Phys. (Paris), Colloq. **45**, C4-433 (1984).

[19]S. J. Seestrom-Morris *et al.*, Phys. Rev. C **26**, 594 (1982).

[20]T. S. H. Lee and D. Kurath, Phys. Rev. C **22**, 1670 (1980).

[21]Isospin conservation requires equal $^{13}$C$(p,\pi^\pm)$ cross sections for mirror $T=2$ states, where the transitions must proceed through a pure $(T_{\rm tot}=1,\ T_3=0)$ overall isospin channel. In such a case, our general TNM arguments (insofar as they are couched in an $n$-$p$, rather than isospin, representation) must be applied with caution. Thus, the $\sigma_{11}$ $pn\rightarrow pp\pi^-$ amplitude, which may drive most $(p,\pi^-)$ transitions, could not contribute at all for a $T=2$ $^{14}$O state, since the required intermediate state $[(pn)_{T=1}+{}^{12}\mathrm{C}^*_{T=1}]$ cannot couple to $T_{\rm tot}=1$. However, $nn\rightarrow(np)_{T=1}\pi^-$ processes [which usually contribute to $(p,\pi^-)$ only via explicit *three*-nucleon involvement] may be important in this case, as the $T_{\rm tot}=1$ component of the entrance channel is an equal admixture of $p+{}^{13}$C and $n+{}^{13}$N.