COMPARISON OF THE $^{13}C(\vec{p},\pi^{\pm})$ REACTIONS TO HIGH EXCITATION ENERGY

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Recent studies at IUCF have demonstrated the dominance of two-nucleon ($NN \rightarrow NN\pi$) production processes and a striking selectivity for high-spin, 2p-1h (with respect to the target nucleus ground state) discrete final states in (p,π^-) reactions.[1,2] This selectivity results from the combination of a highly restrictive reaction path for (p,π^-) transitions (the only contributing NN process is $pn \rightarrow pp\pi^-$ on a target neutron from a specific shell model orbital) and the large momentum mismatch characteristic of exclusive (p,π) reactions. Confirmation for the dominance of this two-nucleon mechanism (TNM) comes from its successful embodiment in model calculations performed recently by Brown et al.[3]: the major features of observed (p,π^-) spectra for nuclei in the $f_{7/2}$- shell region have been reproduced well by these calculations. The population of high-spin 2p-1h states in (p,π^+) reactions is not in general as selective as in (p,π^-), since (p,π^+) transitions of lower angular momentum transfer are often enhanced by coherent contributions from different NN processes ($pp \rightarrow d\pi^+$, $pp \rightarrow np\pi^+$, $pn \rightarrow nn\pi^+$) involving target nucleons from a variety of orbitals. However, companion measurements of (p,π^-) reactions, populating mirror final nuclei where possible, can aid in identifying high-spin transitions in measured (p,π^+) spectra. Because the (p,π^+) transitions with large angular momentum transfer occur generally by more restricted reaction paths than those to low-spin states, one may be able to use the quantum numbers and/or configurations of selected high-spin final states as a "filter" to isolate the effects of specific $NN \rightarrow NN\pi$ isospin channels in the nuclear medium. In an attempt to pursue such possibilities, we have measured cross sections and analyzing powers for $^{13}C(\vec{p},\pi^+)$ and $^{13}C(\vec{p},\pi^-)$ transitions to final states up to 25 MeV excitation energy in the mirror nuclei ^{14}C and ^{14}O. The measurements were made with the QQSP spectrometer, for lab angles between 30° and 150°, at a bombarding energy T_p=200 MeV.

Some of the high-spin configurations that should be accessible via two-nucleon processes in the $^{13}C(p,\pi^{\pm})$ reactions are shown in Table I. It is not expected that all of these would be populated with comparable strength, even in the absence of angular momentum matching considerations. Measurements of pion production in free two-nucleon collisions indicate[4] that by far the strongest channels near threshold are those where the incident nucleons are coupled to isospin T_i=1 and the final nucleons to T_f=0 -- i.e., $pp \rightarrow d\pi^+$ and $pp \rightarrow (np)_{T=0}\pi^+$. Processes for which T_i=1 and T_f=1 -- i.e., $(pn)_{T=1} \rightarrow pp\pi^-$, $(pn)_{T=1} \rightarrow nn\pi^+$, and $pp \rightarrow (np)_{T=1}\pi^+$ -- are weaker by about an order of magnitude in the free NN case. The other possible isospin channel, $T_i=0$ and $T_f=1$, is negligible near threshold. The observation that (p,π^+) cross sections on nuclei are often an order of magnitude stronger than (p,π^-) cross sections suggests that this strength hierarchy of the various $NN \to NN\pi$ isospin channels applies at least qualitatively to production inside nuclei as well as to the free NN case. Thus, those transitions in Table I which require interaction of the incident proton with a target neutron (i.e., all (p,π^-) and selected (p,π^+) transitions) are likely to be considerably weaker than the others. In addition, one should expect population of T=2 final states in $^{13}C(p,\pi^+)^{14}C$ to be relatively weak, since these transitions cannot proceed by the strongest $(T_f=0)$ $NN\pi$ channels. It is of interest to study such weak

Table I. Some High-Spin Configurations in ^{14}C and ^{14}O Accessible via Two-Nucleon Processes^{a)} in $^{13}C(p,\pi^\pm)$

Nucleus	J^π	Configuration	E_x [b] (MeV)	Accessible [a] via Interaction With
^{14}C	3^-	$\lvert ^{12}C \times (\nu p_{1/2})(\nu d_{5/2})\rangle$	6.73	any n or p
^{14}O	3^-	$\lvert ^{12}C \times (\pi p_{1/2})(\pi d_{5/2})\rangle$	6.27	$p_{1/2}$ neutron
^{14}C	4^+	$\lvert ^{12}C \times (\nu d_{5/2})^2\rangle$	10.74	$p_{1/2}$ neutron
^{14}O	4^+	$\lvert ^{12}C \times (\pi d5/2)^2\rangle$	9.92	$p_{1/2}$ neutron
^{14}C	4^-	$\lvert ^{12}C \times (\nu p_{1/2})^2_{0+}(\nu p_{3/2})^{-1}(\nu d_{5/2})\rangle$	11.67	$p_{3/2}$ neutron
^{14}O	4^-	$\lvert ^{12}C \times (\pi p_{1/2})^2_{0+}(\pi p_{3/2})^{-1}(\pi d_{5/2})\rangle$	?	none
^{14}C	4^-	$\lvert ^{12}C \times (\nu p_{1/2})^2_{0+}(\pi p_{3/2})^{-1}(\pi d_{5/2})\rangle$	17.26	$p_{3/2}$ proton
^{14}O	4^-	$\lvert ^{12}C \times (\pi p_{1/2})^2_{0+}(\nu p_{3/2})^{-1}(\nu d_{5/2})\rangle$	?	none
^{14}C	5^-	$\lvert ^{12}C \times (\pi p_{3/2})^{-1}(\pi p_{1/2})(\nu p_{1/2})(\nu d_{5/2})\rangle$	?	$p_{3/2}$ proton
^{14}O	5^-	$\lvert ^{12}C \times (\nu p_{3/2})^{-1}(\nu p_{1/2})(\pi d_{1/2})(\pi d_{5/2})\rangle$	?	$p_{3/2}$ neutron

a) The possible two-nucleon processes considered, and the types of configuration they can lead to in $^{13}C(p,\pi^\pm)$ are:

$$p + p \to n + p + \pi^+ \to \lvert ^{12}C \times (\nu p_{1/2})(\nu \ell j)(\pi \ell' j')(\pi \ell'' j'')^{-1}\rangle$$

$$p + n \to n + n + \pi^+ \to \lvert ^{12}C \times (\nu p_{1/2})(\nu \ell j)(\nu \ell' j')(\nu \ell'' j'')^{-1}\rangle$$

$$p + n \to p + p + \pi^- \to \lvert ^{12}C \times (\nu p_{1/2})(\nu \ell j)^{-1}(\pi \ell' j')(\pi \ell'' j'')\rangle$$

The last column lists the orbital necessary for the struck nucleon in order to reach the specified configuration. Where "none" is indicated, the configuration is inaccessible via two-nucleon processes.

b) Excitation energy of known states with the specified J^π, probably associated primarily with the indicated configuration.

transitions and compare their behavior to that of (p,π^+) transitions dominated by the stronger $NN \rightarrow NN\pi$ isospin channels in order to probe the role of the fundamental process in determining features of pion production from nuclei.

Typical broad-range spectra acquired with a single momentum bite of the QQSP spectrograph for the $^{13}C(p,\pi^{\pm})$ reactions are shown in Fig. 1. Examination of the strongly populated discrete states in these spectra confirms some of our expectations and suggests spectroscopic applications of the results, but also raises some interesting questions. Among the known low-lying states, those with low spin (e.g., 0^+ and 1^-) are stronger in comparison with the high-spin (e.g., 3^-) states in (p,π^+) than in (p,π^-). This observation is in qualitative agreement with our expectations, based on the possible coherent contributions from many reaction paths for low-spin (p,π^+) transitions. In contrast, all (p,π^-) transitions to specific 2p-1h final configurations are restricted to a single reaction path, so that the relative population of different states is dominated by angular momentum matching considerations. Thus, when peaks at similar excitation in ^{14}C and ^{14}O are strong in both spectra in Fig. 1, they most probably correspond to high-spin mirror states accessible in both reactions. The strongly populated 3^- states near E_x=6.5 MeV provide a good example.

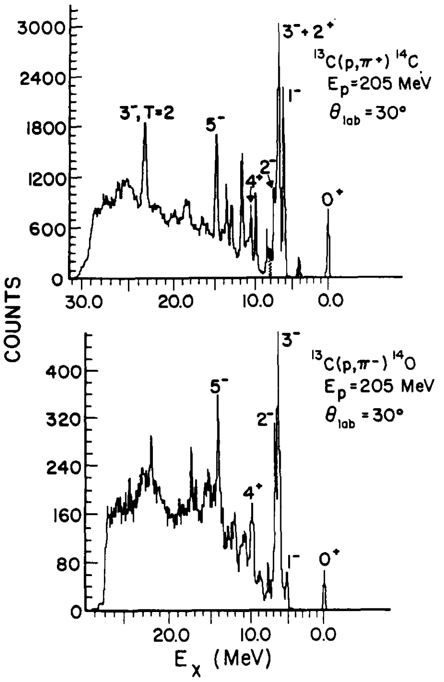

Figure 1. Comparison of typical $^{13}C(p,\pi^{\pm})$ spectra, populating the mirror nuclei ^{14}C and ^{14}O. Some states, labeled by their quantum numbers, are discussed in the text.

The next most strongly populated pair of states in the spectra of Fig. 1, at E_x=14.87 MeV in ^{14}C and E_x=14.15 MeV in ^{14}O, are not known from previous work.[5] Their separation in excitation energy is consistent with that between the known pairs of mirror states at lower excitation. Their strong population in both (p,π^+) and (p,π^-), together with a number of other features, suggest that these correspond to the anticipated 5^- configurations listed in Table I. These configurations could only be reached by 2p-2h excitations from the ^{14}C and ^{14}O ground states, accounting for the failure to observe any high-spin state at this excitation in $^{14}C(e,e')$ (Ref. 6) and $^{14}C(\pi,\pi')$ (Ref. 7) measurements at large momentum transfer (q). On the other hand, the analog 5^-, T=1 configuration in ^{14}N should be excited strongly in inelastic scattering from the 1^+ ground state via a 1p-1h $[(\pi d_{5/2})(\pi p_{3/2})^{-1}]$ proton excitation; indeed, the strongest state seen[6] in $^{14}N(e,e')$ at large q corresponds to an M4 transition at just the appropriate excitation energy (E_x=16.91 MeV) for the isobaric analog of the 14.87 MeV state in ^{14}C. Additional evidence for the 5^- assignment to these states comes from the cross section angular distribution for the

(p,π^+) transition. This distribution falls off more slowly with increasing angle than those for known states of lower spin (<3) and, as seen in Fig. 2, is nearly identical in shape to that measured previously[8] for the $^{12}C(p,\pi^+)$ transition to the known $9/2^+$ 2p-1h state at E_x=9.5 MeV in ^{13}C. The latter transition involves the same basic rearrangement of nucleons, $(\pi p_{3/2}) \rightarrow [(p_{1/2})(d_{5/2})]_{3^-,T=0}$, as does the postulated transition to the 5^- state in ^{14}C, only without the extra $p_{1/2}$ neutron in ^{13}C acting as a spectator.

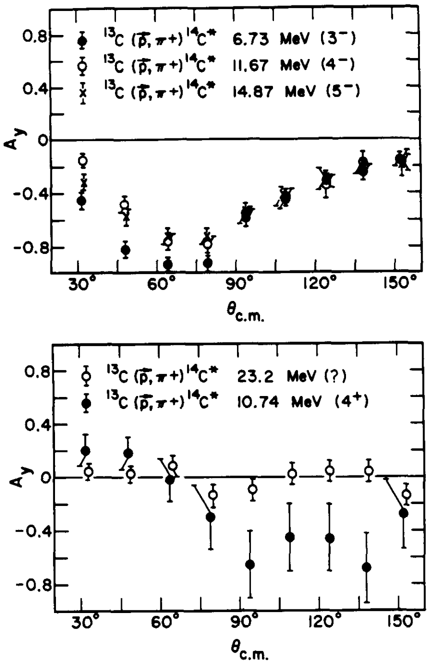

Figure 3. Analyzing power measurements for $^{13}C(\vec{p},\pi^+)$ transitions to some excited states in ^{14}C, showing the great similarity in A_y behavior among transitions that are accessible via the strong $NN \rightarrow NN\pi$ isospin channels, along with results for two anomalous transitions discussed in the text.

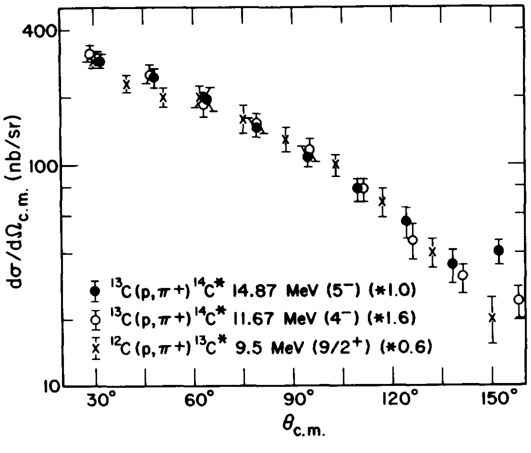

Figure 2. Comparison of cross section angular distributions measured for $^{13}C(p,\pi^+)$ transitions to the excited states at E_x = 14.87 MeV (5^-) and 11.67 MeV (4^-) (multiplied by 1.6), and for $^{12}C(p,\pi^+)$ to the $9/2^+$ state at E_x = 9.5 MeV (multiplied by 0.6). The ^{12}C results are plotted not at the angle where they were actually measured, but at the slightly shifted angles where $^{13}C(p,\pi^+)$ kinematics would give the same momentum transfer as appropriate for the ^{12}C measurements.

The interpretation of other strongly populated discrete states at high excitation in the spectra of Fig. 1 does not fit together so easily with information available from other reactions. The strong (p,π^+) peak at E_x=11.7 MeV is characterized by cross section (Fig. 2) and analyzing power (Fig. 3) distributions nearly identical to that of the 14.87-MeV state discussed above, and so probably corresponds to the 4^- state at E_x=11.67 MeV known from pion[7] and electron[6] inelastic scattering. Both the 4^- and 5^- states would presumably be populated in (p,π^+) via $\Delta L=4$, $\Delta S=1/2$ 2p-1h transitions from the ^{13}C ($1/2^-$) ground state. The (π,π') results suggest[7] that the 11.67 MeV state is predominantly the neutron p-h excitation specified in Table I, but that this is admixed with a proton p-h amplitude (of the sort listed in Table I for the E_x=17.3 MeV state) about 1/3 as large. The 4^- state at 17.3 MeV appears to be predominantly the proton p-h excitation,[7] but does not show up at all in the (p,π^+) spectrum. This situation is reversed from our simple expectations discussed above, since the free $NN \rightarrow NN\pi$ cross sections would suggest much stronger (p,π^+) population of the proton excitation! It is conceivable that one or both of these 4^- states also have appreciable admixtures of the 2p-2h amplitude associated in Table I with the 5^- state, and that the (p,π) results reflect interference among these various amplitudes. Additional constraints which need to be considered in quantifying any such interpretation include the absence of the 4^-, T=2 state (E_x=24.5 MeV, Ref. 6) from the (p,π^+) spectrum, and the sensitivity of $^{13}C(p,\pi^-)$ and $^{14}N(e,e')$ to the 2p-2h admixtures in the 4^- states. There is certainly no dominant feature of the $^{13}C(p,\pi^-)$ spectrum in Fig. 1 which mirrors the 11.7-MeV (p,π^+) peak.

Another puzzle concerns the strong (p,π^+) peak seen at E_x=23.2 MeV (see Fig. 1), with a possible mirror counterpart near 22 MeV excitation in the (p,π^-) spectrum. It is tempting to interpret such a sharp peak at such high excitation as a T=2 state. The excitation energy does not agree with the 2^- (E_x=22.3 MeV) or 4^- (24.5 MeV) T=2 states seen in back-angle $^{14}C(e,e')$ spectra,[6] but would be about right for a 3^-, T=2 state, based on tentative spin-parity assignments[5] for low-lying states in the isobaric nuclide ^{14}B. However, as we argued above, free NN→NNπ results lead one to expect quite weak population of T=2 states in $^{13}C(p,\pi^+)$. Perhaps we are seeing a considerably isospin-mixed state, or a T=1 high-spin state inaccessible via (e,e′) on ^{14}C or ^{14}N (e.g., $|^{13}C \times (\pi p_{3/2})^{-1}(\pi d_{5/2})(\nu d_{5/2})\rangle 6^+, 7^+$).

The mystery of the 23.2 MeV state is compounded by the systematic behavior of analyzing powers (A_y) for the $(\vec{p},\pi^+)$ reaction. Examination of the spin-sum and spin-difference spectra for $^{13}C(\vec{p},\pi^+)$ shown in Fig. 4 reveals that nearly all of the discrete states, as well as the continuum, exhibit a large, negative A_y. This is true at all angles, as can be seen from the typical A_y distributions shown for the 3^-, 4^-, and 5^- states of ^{14}C in Fig. 3. It has been previously noted[9] that most $(\vec{p},\pi^+)$ transitions show very similar A_y patterns, reminiscent of results for $\vec{p}p \to d\pi^+$, presumably reflecting again the dominance of the NN→NNπ channels

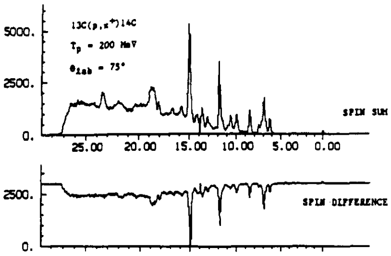

Figure 4. Typical spin-sum (proportional to the cross section) and spin-difference (proportional to the cross section times the analyzing power) spectra for $^{13}C(\vec{p},\pi^+)^{14}C$. The spin-difference spectrum shows the large negative analyzing powers for the continuum and most sharp states.

with T_f=0. These channels cannot contribute to the $(\vec{p},\pi^-)$ reaction, and indeed the A_y behavior for $^{13}C(\vec{p},\pi^-)$ transitions to discrete states and to the continuum (for which A_y is usually close to zero) is totally different from the $(\vec{p},\pi^+)$ pattern. Interestingly, the A_y behavior for the 23.2-MeV $^{13}C(\vec{p},\pi^+)$ peak is also completely different from the standard $(\vec{p},\pi^+)$ pattern, as evidenced by the "disappearance" of this peak in the spin-difference spectrum of Fig. 4 and by its A_y distribution plotted in Fig. 3. Does this result imply that the 23.2-MeV state is not dominated by the T_f=0 NNπ channels (recall that these could not contribute for a T=2 state)? The answer is not yet clear, but it is worth noting that we have extracted cross section and analyzing power data for one $^{13}C(\vec{p},\pi^+)$ transition to a known state where we believe that the T_f=1 channel dominates, namely, the 4^+ state at E_x=10.74 MeV in ^{14}C. This state is most likely reached by a $(\nu p_{1/2}) \to (\nu d_{5/2})^2 4^+$ transition. Its analyzing power (see Fig. 3) again strongly deviates from the usual pattern. On the other hand, its cross section is also much smaller than that for the 23.2 MeV state, and is consistent in order of magnitude with $^{13}C(p,\pi^-)$ transitions, which proceed by the mirror two-nucleon channel $pn \to pp\pi^-$.

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 $NN \to NN\pi$ 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 $(\vec{p},\pi^+)$ 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