Evidence for the quasifree character of the ($\pi^{\pm},\pi N$) reactions on ^{12}C, ^{24}Mg, and ^{40}Ca

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Cross sections for ($\pi^{\pm},\pi N$) reactions near the Δ(1232) resonance on ^{12}C, ^{24}Mg, and ^{40}Ca leading to mirror levels in ^{11}C/^{11}B, ^{23}Mg/^{23}Na, and ^{39}Ca/^{39}K, respectively, were measured by observing their γ decays. σ_n/σ_p for the first $1/2^-$ levels in ^{11}C/^{11}B is 1.4 ± 0.2 for π^- and $1/1.8\pm0.2$ for π^+. For ^{23}Mg/^{23}Na and ^{39}Ca/^{39}K, the ratios are generally not as closely reciprocal as for ^{11}C and the previously reported ^{15}O/^{15}N $3/2^-$ level case. The most strongly excited mirror level pairs are those with large (p,d) and (^{3}He,d) spectroscopic factors. The results are interpreted as evidence for the quasifree character of these ($\pi,\pi N$) reactions.

[NUCLEAR REACTIONS C, Mg, Ca($\pi^{\pm}$, πN), $E=200$ MeV; detected γ's, Ge(Li); measured 90° σ for residual mirror levels; deduced σ ratios.]

Recent activation studies of ($\pi^{\pm}$, πN) reactions[1-3] have resolved in part the puzzle posed by earlier work,[4] in which the activation cross-section ratios $\sigma_{\pi^-}/\sigma_{\pi^+}$ for n removal from ^{12}C, ^{14}N, and ^{16}O near the Δ(1232) π-N resonance were reported to be of the order of 1.0, rather than 3 as expected from the π-N cross section at the resonance. The recently measured activation ratios are 1.55 for ^{12}C (Ref. 1) and 1.68 for ^{14}N and ^{16}O (Ref. 2)—closer to the expected value but still 40–50% below it. Since the excitation curves follow the shape of the Δ(1232) resonance,[1-4] it has been assumed that the reaction is basically a one-step quasifree (OSQF) one. The remaining departure from the πN cross-section ratio has been considered to be due to nuclear effects on the outgoing particles, but the details are still uncertain.[2,5,6]

In a previous study, we detected the γ rays from residual nuclei in ($\pi^{\pm}$, πN) reactions on ^{16}O,[7] so that we were able to determine cross-section ratios for both n and p removal resulting in ^{15}O/^{15}N mirror levels. We found that, at the Δ(1232) resonance, $(\sigma_n/\sigma_p)_{\pi^-}=1.7$ and $(\sigma_n/\sigma_p)_{\pi^+}=1/1.8$ for the first $\frac{3}{2}^-$ level and that the most strongly excited mirror level pairs are those with large spectroscopic factors for (p,d) and (d, ^{3}He) reactions, in support of an OSQF mechanism. Our cross section for $\pi^{\pm}$ induced n removal are, however, only ~25% of the total $\pi^{\pm}$ induced n removal as determined in a subsequent activation experiment,[2] rather than ~60% as expected from consideration of spectroscopic factors. More recently, Morris *et al.*[8] found that the excitation curves for these mirror levels also follow the Δ(1232) resonance, which further supports the conclusion that an OSQF mechanism is operative in ^{16}O ($\pi^{\pm}$, πN).

We have tested this conclusion for several additional ($\pi^{\pm}$, πN) reactions in the Δ(1232) resonance region. We confined our attention to reactions that lead to mirror levels, because their similarity in nuclear structure provides a basis for meaningful comparison.

The experiments were performed with π^- and π^+ beams from the SREL synchrocyclotron. Their design, intensity, lepton contamination, and duty factor is described in Refs. 7, 9, and 10. The natural targets were made as thick as possible without causing excessive γ-ray absorption and pion energy degradation (5.9 and 8.2 g/cm^2, respectively, for π^- and π^+ on carbon, 3.1 and 11.3 g/cm^2, respectively, for π^- and π^+ on magnesium metal, and 5.8 g/cm^2 for both π^- and π^+ on calcium turnings). The average energy in the targets $(E_{in}+E_{out})/2$ was ~220 MeV for the π^- and ~180 MeV for the π^+ beam. [Pion excitation curves generally vary by <10% over the interval $180 \leqslant E_\pi \leqslant 220$ MeV

(Refs. 1–4, and 8).]

The γ rays were detected with an ~20% efficient Ge(Li) detector for π^- on ^{12}C and ^{24}Mg and with an ~8% efficient Ge(Li) detector for all other reactions, at ~90° with respect to the beam. Events coincident with the beam telescope and anticoincident with a scintillator surrounding the Ge(Li) detector (to discriminate against charged particles) were energy-analyzed and stored in the first half of a multichannel analyzer. Background and random contributions to a spectrum were identified by recording, in the second half of the analyzer, an additional spectrum consisting of events in the Ge(Li) detector that were delayed by ~150 nsec relative to beam-telescope events. Overall system resolution was ~5 keV at 1 MeV. Further details are given in Refs. 7, 9, and 10.

In the resulting γ-ray spectra, numerous peaks were identified with known transitions[11,12] in residual nuclei due to single and multinucleon removal, inelastic scattering, and charge exchange.[7,9,10] Portions of the $\pi^\pm + {}^{12}C$ spectra are shown in Fig. 1. The peaks in the $\pi^\pm + {}^{24}Mg$ and $\pi^\pm + {}^{40}Ca$ spectra were considerably less Doppler broadened than those shown and hence were much easier to analyze.

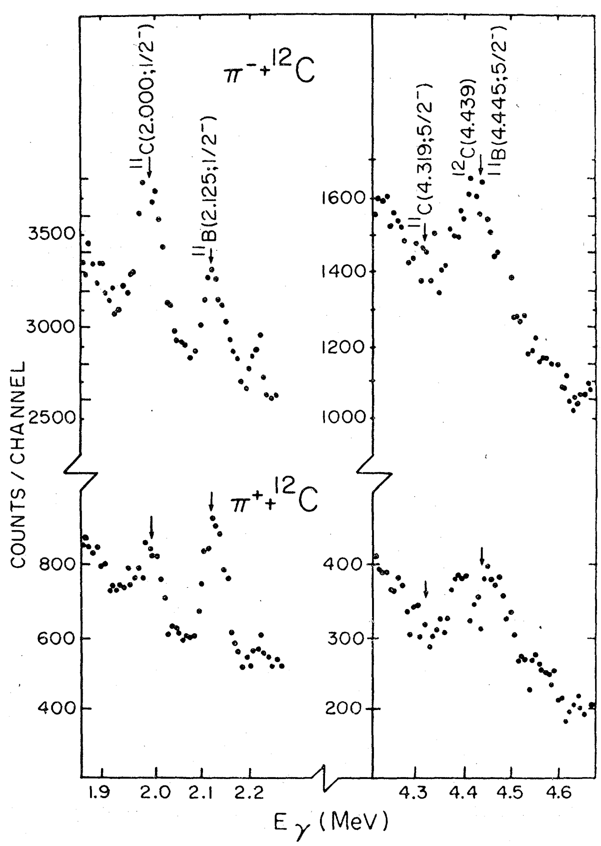

FIG. 1. Portions of the prompt γ-ray spectra from interactions of 220 MeV π^- and of 180 MeV π^+ with ^{12}C. Arrows indicate nominal photopeak positions.

The single-nucleon removal cross sections calculated from the peaks are given in Table I. Our previous results for ^{16}O (Ref. 7) are given for comparison. These cross sections have been corrected for γ-ray feeding from higher energy levels known to be excited, for target γ-ray absorption, and for efficiency, assuming isotropic γ emission. Also shown are percentage spectroscopic factors for the analogous n and p removal reactions (p,d) (Refs. 13 and 14) and $(d, {}^3He)$ (Refs. 15 and 16) and cross-section ratios for n to p removal. While the absolute uncertainty in cross sections determined by the γ-ray technique is of the order of 20%, the uncertainty in the ratios for two mirror levels is only statistical.

For $^{12}C\ (\pi^\pm, \pi N)$, the only mirror states that were clearly identified were the $^{11}C/^{11}B$ first excited $\frac{1}{2}^-$ states (see Fig. 1). Morris *et al.*,[8] in their NaI γ-ray experiment, detected a transition at 4.37 MeV which they identified as the shared strength of the deexcitation of the $\frac{5}{2}^-$ mirror levels at 4.319 MeV in ^{11}C and 4.445 MeV in ^{11}B. In their experiment, however, this peak may also be due to deexcitation of the ^{12}C 4.439 MeV level, which is excited by (π,π') or (n,n') scattering. Although they calculate the (π,π') cross section to be less than 20% of this peak and conclude that (n,n') can be ruled out because their γ-ray yield for this transition increased linearly with target thickness, our Fig. 1 clearly shows that the large peak at this energy is not the ^{11}C 4.319 MeV transition. Furthermore, in a run in which the target thickness was increased by 50%, we found that the yield of the peak at 4.44 MeV increased by a larger factor than 1.5^2, indicating a strong (n,n') contribution and hence a likely (π,π') assignment. A $^{12}C\ (\pi,\pi p)^{11}B$ contribution cannot be ruled out, but it is expected to be small because of the low upper limit of the mirror transition in ^{11}C (Table I and Fig. 1).

Dropesky *et al.*, in their activation measurement,[1] found the total cross section to be 70 mb for $^{12}C\ (\pi^-, \pi^- N)$ at 220 MeV and 43 mb for $^{12}C\ (\pi^+, \pi N)^{11}C$ at 180 MeV. Our cross sections for the first excited state of ^{11}C (Table I) thus represent ~10% of the activation yield for all bound states. This is consistent with the 13% spectroscopic factor from $^{12}C(p,d)^{11}C$ for that level and with the lack of detected excitation of other ^{11}C states in our work. The ratios are not 3 and $\frac{1}{3}$ as predicted by the OSQF mechanism, but they do display the reciprocity found for the $^{16}O(\pi^\pm, \pi N)$ reactions leading to the $\frac{3}{2}^-$ mirror states in $^{15}O/^{15}N$.

For both $^{12}C(\pi^\pm, \pi N)$ and $^{16}O(\pi^\pm, \pi N)$, most of the

TABLE I. Cross sections and ratios for $(\pi^{\pm}, \pi N)$ reactions near $\Delta(1232)$ resonance leading to mirror levels in residual nuclei.

Target (J^{π}, $T=0, 0$)	Residual nucleus level ($T=\frac{1}{2}$)	Spectroscopic factor	σ_{π^-} (mb)	$\left(\frac{\sigma_n}{\sigma_p}\right)_{\pi^-}$	σ_{π^+} (mb)	$\left(\frac{\sigma_n}{\sigma_p}\right)_{\pi^+}$
^{12}C	^{11}C(2.000 MeV, $\frac{1}{2}^-$)	0.59 [a]	6.2 ± 1.1	1.4 ± 0.2	4.5 ± 0.9	$\frac{1}{1.8 \pm 0.2}$
	^{11}B(2.125 MeV, $\frac{1}{2}^-$)	b	4.9 ± 0.9		8.2 ± 1.5	
	^{11}C(4.319 MeV, $\frac{5}{2}^-$)	0 [a]	<1.9 [g]		<2.7 [g]	
	^{11}B(4.445 MeV, $\frac{5}{2}^-$)	b	f		f	
	^{11}C(4.804 MeV, $\frac{3}{2}^-$)	0.37 [a]	<2.9		<4.0	
	^{11}B(5.021 MeV, $\frac{3}{2}^-$)	b	<2.6		<2.8	
^{16}O	^{15}O(5.242 MeV, $\frac{5}{2}^+$)	0 [a]	2.9 ± 0.8	0.7 ± 0.2	2.3 ± 0.7	$\frac{1}{2.1 \pm 0.8}$
	^{15}N(5.271 MeV, $\frac{5}{2}^+$)	0.31 [c]	4.2 ± 1.1		4.8 ± 1.4	
	^{15}O(6.177 MeV, $\frac{3}{2}^-$)	3.8 [a]	15.6 ± 3.8	1.7 ± 0.4	9.9 ± 2.8	$\frac{1}{1.8 \pm 0.4}$
	^{15}N(6.323 MeV, $\frac{3}{2}^-$)	3.72 [c]	9.1 ± 2.5		17.3 ± 0.4	
^{24}Mg	^{23}Mg(0.451 MeV, $\frac{5}{2}^+$)	5.7 [d]	27.3 ± 5.4	0.8 ± 0.2	14.1 ± 3.0	$\frac{1}{1.7 \pm 0.2}$
	^{23}Na(0.440 MeV, $\frac{5}{2}^+$)	3.8 [e]	33.3 ± 6.4		23.6 ± 3.7	
	^{23}Mg(2.051 MeV, $\frac{7}{2}^+$)	0 [d]	<3.0		<6.4	
	^{23}Na(2.076 MeV, $\frac{7}{2}^+$)	0 [e]	f		f	
	^{23}Mg(2.359 MeV, $\frac{1}{2}^+$)	0.20 [d]	2.8 ± 0.8	0.8 ± 0.2	<1.6	
	^{23}Na(2.391 MeV, $\frac{1}{2}^+$)	0.3 [e]	3.6 ± 1.5		3.2 ± 1.0	
	^{23}Mg(2.771 MeV, $\frac{1}{2}^-$)	3.4 [d]	10.8 ± 2.7	2.2 ± 0.5	8.6 ± 1.8	$\frac{1}{1.2 \pm 0.2}$
	^{23}Na(2.640 MeV, $\frac{1}{2}^-$)	2.6 [e]	5 ± 1.3		10.2 ± 1.9	
^{40}Ca	^{39}Ca(2.472 MeV, $\frac{1}{2}^+$)	3.6 [d]	13 ± 3	1.6 ± 0.5	9 ± 2	$\frac{1}{1.8 \pm 0.3}$
	^{39}K(2.523 MeV, $\frac{1}{2}^+$)	3.2 [c]	8 ± 3		16 ± 4	
	^{39}Ca(2.793 MeV, $\frac{7}{2}^-$)	1.2 [d]	11 ± 2	1.2 ± 0.3	5 ± 1	$\frac{1}{3.4 \pm 0.4}$
	^{39}K(2.814 MeV, $\frac{7}{2}^-$)	0.92 [c]	9 ± 3		17 ± 4	

[a] S from (p,d) (Ref. 13).
[b] Spectroscopic information not available.
[c] C^2S from $(d, {}^3\mathrm{He})$ (Ref. 15).
[d] S from (p,d) (Ref. 14).
[e] C^2S from $(d, {}^3\mathrm{He})$ (Ref. 16).
[f] σ could not be determined because of overlapping peaks.
[g] Upper limit estimated from second escape peak region (not shown in Fig. 1).

spectroscopic strength should go to the ground state and the low excited states, if the reactions are of an OSQF nature. In that case, γ-ray feeding from higher states is negligible, and the cross-section ratios can be determined quite unambiguously. For $^{24}\mathrm{Mg}(\pi^{\pm}, \pi N)$, however, about 35% of the reported spectroscopic strength from (p, d) (Ref. 14) lies in the excited states above the first four. Transitions from these higher excited states could not be detected in our experiment because of lower detector efficiency and greater line width at the higher γ-ray energies. Therefore, we were unable to correct for the expected feeding from these states to the lower excited states. This may be why the cross sections for ^{24}Mg (Table I) do not show the reciprocity observed for the first excited states in ^{12}C and ^{16}O. However, the strong excitations of the $\frac{5}{2}^+$ and $\frac{1}{2}^-$ states and the weak excitations of the $\frac{7}{2}^+$ and $\frac{1}{2}^+$ states are indications that this reaction may also proceed by an OSQF mechanism.

In the $^{40}\mathrm{Ca}(\pi^{\pm}, \pi N)$ reaction, the first two ^{39}Ca/^{39}K mirror states are excited approximately equally, but no other states are seen. In the $^{40}\mathrm{Ca}(p, d)^{39}\mathrm{Ca}$ reaction, ~38% of the reported spectroscopic strength[14] is in the ground states, ~19% in the first excited state, ~6% in the second excited state, and ~37% in higher excited states. The cross-section ratios for the first ^{39}Ca/^{39}K excited states show reciprocity. This is not true of the second excited state, although the ratios do exhibit inversion. Because of the large spectroscopic strength in several states above the second, there is likely to be considerable γ feeding to lower states, if the reaction is OSQF. Such feeding could account for the nearly equal excitation of the $\frac{1}{2}^+$ and $\frac{7}{2}^-$ states and also for the asymmetry of the $\frac{7}{2}^-$ cross-section ratios. The sum of the observed $^{40}Ca(\pi, \pi N)$ cross sections is only half as large as the sum of the corresponding ^{24}Mg cross sections, possibly because in $^{40}Ca(\pi, \pi N)$ the nucleus is preferably left in the undetected ground state, as expected from the ~38% spectroscopic strength of this state.

In summary, we find that states with large spectroscopic factors for nucleon-induced single-nucleon removal are generally the most strongly excited ones in the $(\pi, \pi N)$ reactions we examined, and that the cross-section ratios exhibit reciprocity in cases where γ-ray feeding from higher states is likely to be significant. These results are in support of an OSQF mechanism. The ratios differ, however, of the order of 50% from the values expected from an OSQF mechanism, and more where feeding contributions are likely to be significant.

Our work, then, shows evidence that an OSQF mechanism is operative for $(\pi, \pi N)$ reactions on several self-conjugate targets. To gain further understanding of the mechanisms involved in such single-nucleon removal reactions, the outgoing nucleons need to be detected with high resolution and in coincidence with either scattered pions or with deexcitation γ rays.

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