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Cross Section Ratios for ($\pi^{\pm}, \pi N$) Reactions on ^{16}O near the $\Delta(1236)$ Resonance*

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Ratios of cross sections for 200-MeV $\pi^{\pm}$ reactions on ^{16}O leading to mirror levels in ^{15}O and ^{15}N, observed by their γ decays, were measured and compared. For the first $\frac{3}{2}^-$ levels, the ratios are $(^{15}\mathrm{O}/^{15}\mathrm{N})_{\pi^-} = 1.7 \pm 0.4$ and $(^{15}\mathrm{O}/^{15}\mathrm{N})_{\pi^+} = 1/(1.8 \pm 0.4)$, indicating charge symmetry.

The one-step quasifree (OSQF) mechanism for $(\pi, \pi N)$ nuclear reactions, in which the incident pion scatters from an individual nucleon, appeared to be a good approximation[1] until Chivers *et al.*[2] reported that the activation-cross-section ratios $(A + \pi^- \to A - 1)/(A + \pi^+ \to A - 1)$ on ^{12}C, ^{14}N, and ^{16}O near the $\Delta(1236)$ pion-nucleon resonance are close to 1 and not to 3, as originally expected from the behavior of the pion-nucleon cross section. Similar cross-section ratios have also been determined for a variety of even- and odd-mass targets from ^{4}He to ^{64}Zn at incident energies ranging from 30 to 360 MeV.[2-9] A recent remeasurement at Los Alamos[10] of $\pi^{\pm}$ activation of ^{11}C from ^{12}C yielded π^+ cross sections somewhat lower than those in Ref. 2. Nearly all ratios were found to be considerably less than 3; the Los Alamos measurement yielded, at $E_\pi = 180$ MeV, $\sigma_{\pi^-}/\sigma_{\pi^+} = 1.5$. Various mechanisms have been proposed to explain these results. Besides OSQF processes, final-state interactions between the struck nucleon and the residual nucleus and inelastic pion scattering to unbound levels have been suggested.[2,11-17]

In order to test the $(\pi, \pi N)$ nuclear reaction mechanism in a different way from previous experiments, we determined, for incident π^+ near the $\Delta(1236)$ resonance energy on a water target, the ratio of π^+ cross sections,

$$R(\pi^+) \equiv \frac{\sigma(\pi^+, {}^{15}\mathrm{O}^*(6.18, \frac{3}{2}^-))}{\sigma(\pi^+, {}^{15}\mathrm{N}^*(6.32, \frac{3}{2}^-))},$$

producing the first $\frac{3}{2}^-$ excited levels in the residual mirror nuclei ^{15}O and ^{15}N. We then compared the result with a previously obtained ratio[18] of π^- cross sections,

$$R(\pi^-) \equiv \frac{\sigma(\pi^-, {}^{15}\mathrm{O}^*(6.18, \frac{3}{2}^-))}{\sigma(\pi^-, {}^{15}\mathrm{N}^*(6.32, \frac{3}{2}^-))},$$

leading to the same excited residual-nucleus levels. These ratios were determined by observing the prompt de-excitation γ rays from individual bound levels of these residual nuclei. Since the decay schemes for ^{15}O and ^{15}N[19] permit an unambiguous determination of the extent to which the first $\frac{3}{2}^-$ levels are populated directly from the reactions rather than from γ-ray feeding, a major uncertainty inherent in the prompt-γ-ray method was avoided.

These $\frac{3}{2}^-$ levels have a predominant $(p_{3/2})^{-1}$ hole configuration. Hence they should be strongly excited if the reaction proceeds by a direct process. In the previous ^{16}O-π^- experiment, these levels were indeed strongly excited. However, $R(\pi^-)$ was found to be 1.7 ± 0.4, i.e., below the OSQF value of 3 but larger than the value of 1.03 ± 0.09 given by Chivers *et al.*[2] for the ratio of activation cross sections,

$$\sigma(^{16}O + \pi^- \to {}^{15}O)/\sigma(^{16}O + \pi^+ \to {}^{15}O),$$

to all bound levels in the residual nucleus ^{15}O. If the reaction proceeds predominantly by an isospin-symmetric process, such as OSQF or a final-state mechanism, then $R(\pi^+)$ should equal $1/R(\pi^-)$. Hence a comparison of these ratios is suggestive of the reaction mechanism.

The experiments were performed with π^- and π^+ beams from the Space Radiation Effects Laboratory synchrocyclotron.[20] The 230-MeV π^- beam was momentum-selected by a bending magnet from pions produced on an internal carbon target, deflected out of the cyclotron by its fringing field, and focused by a quadrupole pair.[18] The 190-MeV π^+ beam was focused and momentum-selected by a beam channel[21] from pions produced by the external proton beam in a CH_4 target; protons in the π^+ beam were stopped in Plexiglas before the last bending magnet. The intensity for both beams, as determined with a counter telescope in front of the experimental target, was of the order of 2×10^5 particles/sec. The lepton contribution was $(15 \pm 7)\%$ in the π^- beam[18] and $(8 \pm 5)\%$ in the π^+ beam,[4] as determined by time-of-flight measurements. The H_2O targets were made as thick as possible without causing excessive γ-ray absorption and pion-energy degradation (15 and 10 g/cm^2, respectively, for π^- and π^+ beams). The water was kept in rectangular, 0.1-mm-thick brass containers. The average energy in the targets, $(E_{in}+E_{out})/2$, was 215 MeV for the π^- beam and 180 MeV for the π^+ beam. (Pion excitation curves for ^{16}O vary by $< 7\%$ over the interval $180 \leq E_\pi \leq 215$ MeV.[2])

Gamma rays were detected with a 40-cm^3 Ge(Li) detector at approximately 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 ~50 nsec relative to beam-telescope events. Overall system resolution was ~5 keV at 1 MeV. Further details are given in Ref. 18.

In the resulting γ-ray spectra, approximately twenty peaks were seen and identified with transitions in residual nuclei. The first excited $\frac{3}{2}^-$ mirror levels in ^{15}O and ^{15}N, together with the 6.131-MeV, 3^-, $T=0$ level in ^{16}O, the 3.945-MeV, 1^+, $T=0$ level in ^{14}N, and the 4.439-MeV, 2^+, $T=0$ level in ^{12}C, were the most strongly excited ones in both the π^-- and the π^+-induced reactions. Portions of the spectra containing the $\frac{3}{2}^-$-level photopeaks are shown in Fig. 1. The width of these peaks is due to Doppler recoil broadening in the target.

From the decay schemes for ^{15}O and ^{15}N,[19] it is evident that γ feeding from higher excited levels does not contribute significantly to the excitation of the first $\frac{3}{2}^-$ mirror levels. In ^{15}O, the three bound levels above the $\frac{3}{2}^-$ level at 6.177 MeV have no reported γ branch to that level, and the small γ widths of the unbound ^{15}O levels cannot contrib-

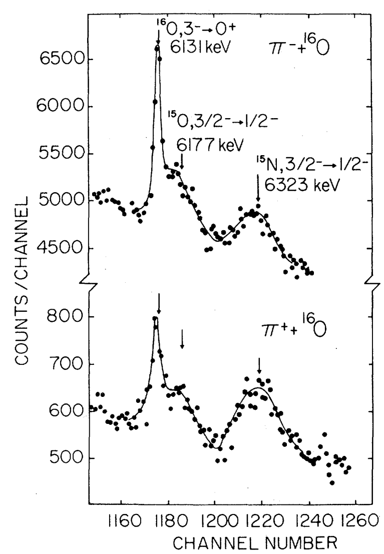

FIG. 1. Portions of the prompt-γ-ray spectra from interactions of 215-MeV π^- and of 180-MeV π^+ with ^{16}O, containing the photopeaks due to ground-state transitions from the ^{15}O and ^{15}N mirror levels near 6 MeV. Arrows indicate nominal photopeak positions; the solid lines are intended to guide the eye.

TABLE I. Experimental cross sections for 215-MeV π^- and 180-MeV π^+ interactions with ^{16}O.

Product	E_{exc} (MeV)	J^π	$\sigma(\pi^-)$ (mb) [a]	$\sigma(\pi^+)$ (mb) [b]
^{15}N	6.323	$(3/2)^-$	9.1 ± 2.5	17.3 ± 4.6
^{15}O	6.177	$(3/2)^-$	15.6 ± 3.8	9.9 ± 2.8
^{15}N	5.271	$(5/2)^+$	4.2 ± 1.1 [c]	4.8 ± 1.4 [c]
^{15}O	5.242	$(5/2)^+$	2.9 ± 0.8 [c]	2.3 ± 0.7 [c]
^{16}O	6.131	3^-	12.5 ± 2.8	9.0 ± 2.3

[a] Ref. 18.

[b] Present work.

[c] Probably includes feeding from higher bound levels; see text.

TABLE II. Cross-section ratios, $R(\pi^\pm)$, for $\pi^\pm + {}^{16}O \rightarrow {}^{15}O, {}^{15}N$ 6-MeV $\frac{3}{2}^-$ states at E_π near the $\Delta(1236)$ resonance.

Reactions	OSQF	Expt.
$\dfrac{\sigma(\pi^+, {}^{15}O^*[6.18, (3/2)^-])}{\sigma(\pi^+, {}^{15}N^*[6.32, (3/2)^-])}$	$\dfrac{1}{3}$	$\dfrac{1}{1.8 \pm 0.4}$
$\dfrac{\sigma(\pi^-, {}^{15}O^*[6.18, (3/2)^-])}{\sigma(\pi^-, {}^{15}N^*[6.32, (3/2)^-])}$	3	1.7 ± 0.4

ute significantly to the excitation of that level. In ^{15}N, there are thirteen bound levels above the $\frac{3}{2}^-$ level at 6.323 MeV. While two of these levels do have branches to the $\frac{3}{2}^-$ level (< 25% each), no significant transitions from these two levels were found in the γ-ray spectra. Of the remaining bound levels, six have γ branches of less than 5%, and five have no reported branching to the $\frac{3}{2}^-$ level. The observed strong excitation of the first $\frac{3}{2}^-$ level is, therefore, attributed primarily to excitation from the reactions rather than to feeding from higher excited levels.

The only other ^{15}O and ^{15}N levels for which transitions could be identified in both the π^+ and π^- spectra were the first excited $\frac{5}{2}^+$ mirror levels near 5 MeV. Although none of the bound negative-parity levels have significant γ branches to these levels, several higher-energy positive-parity bound levels have significant branching to these $\frac{5}{2}^+$ levels.[19] Since the lifetimes of these higher positive-parity levels are short enough (< 0.1 psec) to produce Doppler-broadened γ peaks possibly obscured by spectrum background, the amount of excitation directly to the first $\frac{5}{2}^+$ levels could not be determined.

Cross sections were determined and corrected for target γ-ray absorption, detector efficiency assuming isotropic γ emission, and feeding from higher levels which were found to be excited. The values determined from photopeaks were consistent with values determined from escape peaks. The results are shown in Table I for the first $\frac{3}{2}^-$ and $\frac{5}{2}^+$ levels in ^{15}O and ^{15}N and for the 3^- level in ^{16}O. In Table II, cross-section ratios for the first $\frac{3}{2}^-$ levels are shown. The cross-section errors include both statistical and systematic contributions. In the ratios, transitions of similar energy are compared, so that most systematic error contributions cancel out.

The cross sections for excitation of the first $\frac{3}{2}^-$ levels in ^{15}O and ^{15}N are large, in qualitative agreement with the OSQF prediction. Furthermore, these cross sections display, within error limits, T_z symmetry; i.e., $\sigma(\pi^-)$ for ^{15}O equals $\sigma(\pi^+)$ for ^{15}N, and $\sigma(\pi^+)$ for ^{15}O equals $\sigma(\pi^-)$ for ^{15}N. Hence, within error limits, $R(\pi^+) = 1/R(\pi^-)$ for the first $\frac{3}{2}^-$ levels. It should be noted that these ratios differ by ~50% from the OSQF prediction. Differences of this magnitude have, in fact, been expected from distortion and other effects of the nucleus on the interacting pion and nucleon.[12-14,17]

Relative to the $\frac{3}{2}^-$ cross sections, the cross sections for excitation of the first $\frac{5}{2}^+$ levels are considerably larger than expected from OSQF processes—the experimental $\sigma_{(5/2)^+}/\sigma_{(3/2)^-}$ ratios range from 0.2 to 0.5 (Table I). In a OSQF process, the cross sections would be proportional to the spectroscopic factors for nucleon removal; i.e., $\sigma_{(5/2)^+}/\sigma_{(3/2)^-} = S_{(5/2)^+}/S_{(3/2)^-} < 0.1$.[18,22] (These $\frac{5}{2}^+$ and $\frac{3}{2}^-$ states are predominantly two-hole, one-particle and one-hole states, respectively.[23]) Even with the previously mentioned possibility of unmeasured $\frac{5}{2}^+$ feeding from higher positive-parity levels, having comparably small spectroscopic factors, the measured ratios are larger than expected from OSQF. A final-state process[13,15] could produce the two-hole, one-particle state needed for the positive-parity states. The stronger excitation of ^{15}N $\frac{5}{2}^+$ relative to ^{15}O $\frac{5}{2}^+$ may be due to the presence of about four bound ^{15}N positive-parity levels that appreciably branch to the $\frac{5}{2}^+$ whereas ^{15}O has only one such level.

Estimated ground-state cross sections added to the measured ^{15}O excited-state γ cross sections for $\pi^- + {}^{16}O$ agreed (Ref. 18, Section IV-A) with the π^--^{16}O activation cross sections of Chivers *et al.*[2] Similar agreement is obtained in the present π^+ work if the Chivers *et al.* π^+-^{16}O activation cross section is lowered by ≃30%, as indicated by the Los Alamos π^+-^{12}C remeasurement.[10]

The cross sections for excitation of the 6.131-MeV, 3^- level in ^{16}O are nearly equal, as expected for inelastic scattering from a $T=0$ target.

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(^{6}Li,d) Reaction on fp-Shell Nuclei and Alpha-Transfer Distorted-Wave Born-Approximation Analysis

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Strongly structured (^{6}Li, d) angular distributions exhibiting systematic variations with A for $A=40$ to $A=90$ target nuclei are well reproduced by α-stripping calculations using a single set of potential parameters. Zero-range and finite-range distorted-wave Born-approximation results are found very similar both in the shapes of the angular distributions and in the relative magnitudes. The question of nuclear-structure dependence in the angular distributions is discussed.

The (^{6}Li,d) reaction has been studied on a series of fp-shell nuclei at the University of Rochester.[1,2] In this note we want to demonstrate the capability of the α-transfer distorted-wave Born approximation (DWBA), in a very simple parametrization, to reproduce the highly structured angular distributions for the full range of nuclei investigated. Exact recoil finite-range calcula-