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Gamma rays emitted following the interaction of 230-MeV negative pions with ^{16}O†*

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γ rays have been detected from 230-MeV negative pions incident on a water target. Deexcitation γ rays from ^{10}B, ^{12}C, ^{13}C, ^{14}C, ^{14}N, ^{15}N, ^{15}O, ^{16}O, and ^{16}N have been identified and cross sections for excitation of particular residual states determined. Where necessary, the cross sections have been corrected for γ feeding from higher states. Decays from short lived nuclear states result in Doppler broadened peaks which yield nuclear recoil momenta.

[NUCLEAR REACTIONS $^{16}O(\pi^-, \gamma X)$, $E = 230$ MeV, measured relative γ yields at $\theta = 90°$.]

I. INTRODUCTION

The use of pions as a nuclear probe has been limited by the difficulties inherent in the low intensity and the poor resolution of the beams which, up to now, have been available. In the present work, cross sections for a variety of reactions induced by negative pions on a water target were measured by detecting prompt deexcitation γ rays from the residual nuclei, using a high resolution Ge(Li) detector. This has partially circumvented the above difficulties and has permitted the measurement of discrete nuclear levels populated by pion reactions. The results of this technique are not always unambiguous as it is necessary to interpret complex γ spectra with occasionally overlapping peaks in terms of the known γ branches of the nuclear levels.

II. EXPERIMENT

The experiment was performed at the 600-MeV synchrocyclotron of the NASA Space Radiation Effects Laboratory using the 230-MeV pion beam. The π^- beam was focused by a pair of quadrupole magnets near the cyclotron vacuum tank window and momentum selected by a bending magnet located just upstream of the experimental area adjacent to the cyclotron. Figure 1 shows the experimental setup. The beam passed through a lead collimator, through three beam telescope scintillation counters and was then incident on the target. Water was used for the ^{16}O target and held in a 10.4-cm×10.4-cm×15.7-cm container constructed of 0.01-cm thick brass. Pions entered the target with a nominal 230-MeV energy and were degraded ~30 MeV in their passage through the target. The γ rays were detected by a 40-cm^3 Ge(Li) detector which was surrounded by an anticoincidence scintillator cup to veto charged particles.

Ge(Li) detector signals coincident with signals in the three beam telescope scintillation counters were gated into a 8192 channel analog-to-digital converter with a digital stabilizer. In addition, a delayed coincidence spectrum was taken to aid in the identification of accidentals. A hodoscope of five scintillation counters, labeled A to E in Fig. 1, surrounded the target in an attempt to detect the outgoing π^-. Copper degraders (0.32 cm thick) were placed between the target and counters A, D, and E to aid in the identification of the outgoing charged particles. Separate energy spectra were accumulated for γ rays in coincidence with each of these counters in addition to the total spectrum. Unfortunately this technique could not distinguish between outgoing protons, negative pions, or electrons and positrons from π^0 decays, and the outgoing particle coincident spectra were generally not used in the data analysis.

Spectrum energy calibration was accomplished by using a combination of standard sources, peaks of known energy from the spectra of the water target, and peaks generated by a precision pulser. Relative and absolute photopeak efficiencies of the Ge(Li) detector were determined using standard radioactive sources of known strengths. These efficiencies were extrapolated up to 6 MeV using known yields of pionic x rays studied with the same detector.[1] These efficiency data were fitted to a power law function[2] and corrected for absorption of γ rays in the target.

Several checks were made to verify that the γ

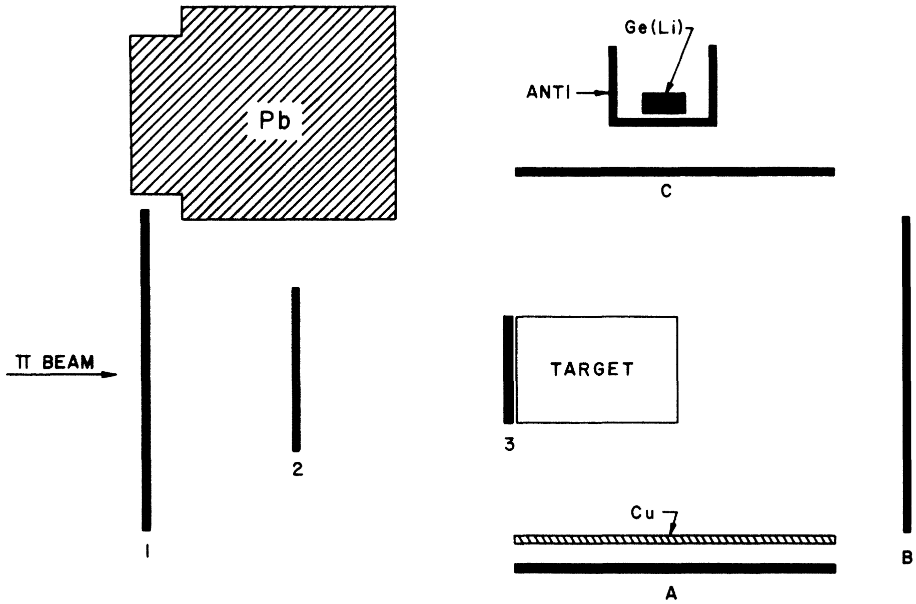

FIG. 1. Diagram of the experimental geometry. Before entering counter 1, the π beam passed through an 20-cm $\times$20-cm lead beam slit. Counters D and E are not shown. Counter D was located above the target, coplanar with the upper edges of counters A and C. Counter E was located below the target, coplanar with the lower edges of counters A and C.

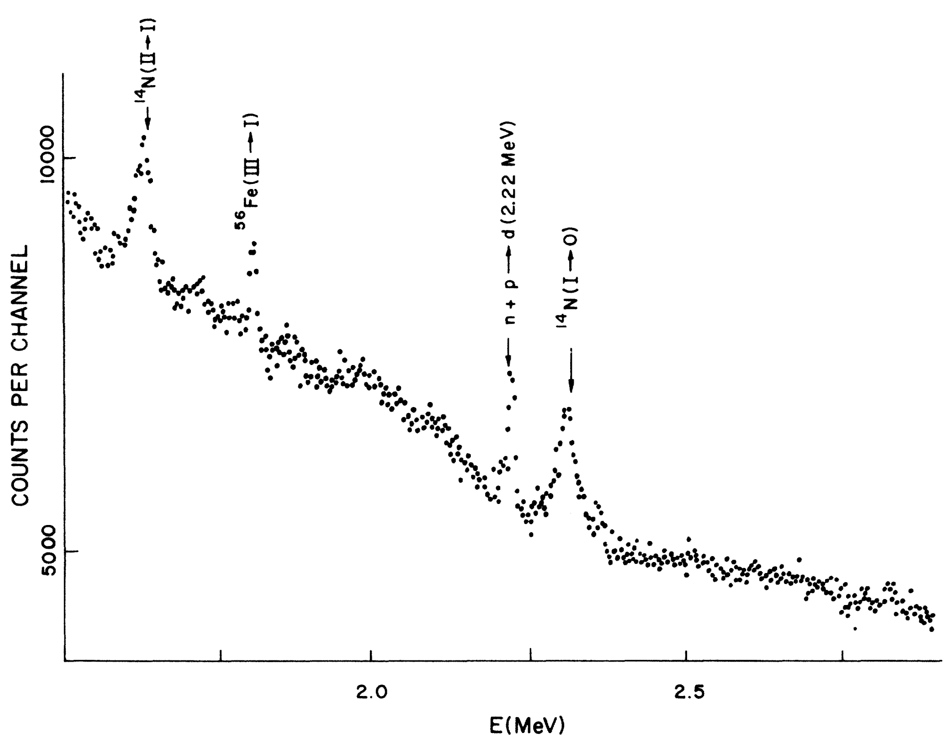

FIG. 2. γ ray spectrum from 230-MeV π^- on a water target. This spectrum covers an energy range of 1.5 to 3.0 MeV. Note displaced zero.

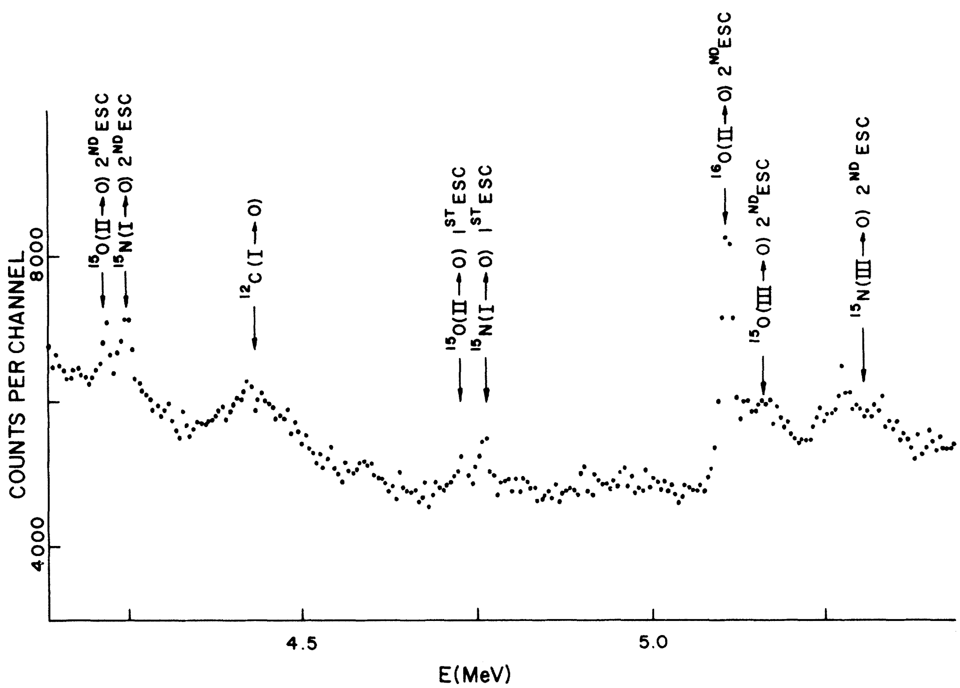

FIG. 3. γ ray spectrum from 230-MeV π^- on a water target. This spectrum covers an energy range of 4.2 to 5.5 MeV. Note displaced zero.

rays of interest were produced only by π^- in the ^{16}O target. This analysis indicated the possible secondary neutron contamination affecting observed transitions in ^{16}O, ^{16}N, ^{13}C, and ^{12}C residual nuclei. The extent of this contamination will be dealt with in Secs. IV C, IV D, and IV E.

γ-ray peaks resulting from the decay of short lived (≤ 1 psec) states showed Doppler broadening due to the recoil momentum of the product nucleus. This was used to aid in the identification of γ peaks in the spectrum and the determination of nuclear recoil momenta.

III. DATA ANALYSIS

Figures 2 and 3 are sample γ-ray spectra from the water target covering two energy regions. The peaks were analyzed using a standard least squares fitting procedure.[3] The cross sections for excitation of discrete states of residual nuclei are reported in Tables I–III at three different stages of analysis to display the extent of γ feeding from higher states.

The cross section for production of a particular γ ray was first calculated by correcting the fitted area of the peak for absorption of γ rays in the target and for detector efficiency assuming isotropic γ emission. From this result, a cross section, β, for production of this γ ray was then calculated in the conventional manner using the number of incident pions and the target parameters. If this γ ray could be attributed to the decay of a state which has several γ branches, β was divided by the branching ratio for that mode of decay yielding a cross section designated as α. An attempt was then made to corroborate this result by locating additional γ-ray peaks resulting from the state's other decay modes. Similar analysis of these peaks by the above procedure was required within the experimental uncertainties to produce the same value of α and thus confirm the assignment. Frequently, however, it was not possible to detect these additional transitions because of such obscuring factors as low branching ratios, large widths due to Doppler broadening, the presence of interfering peaks, or transition energies outside the range of the measured spectra.

As calculated above, α is thus the cross section for production of a particular state either by direct excitation or by γ feeding from higher energy states. The first step in the elimination of γ feeding from higher states corrects for feeding from those higher states for which definite values of α had been measured. The resulting cross section, which we designate as σ_1 for a particular lower state, was obtained by subtracting from α for that state the sum of all the α's for the higher states with γ branches to that state multiplied by the appropriate branching ratios.

In some cases, however, σ_1 is not unambiguously the cross section for direct excitation of a particu-

TABLE I. Cross sections for π^- reactions on ^{16}O resulting in $(A-1)$ residual nuclei.

Residual nucleus [a] (MeV)		π $J;T$	α [b] (mb)	σ_1 [c] (mb)	σ_2 [d] (mb)	ΔP (MeV/c)
^{15}N	5.271	$\frac{5}{2}^+$	4.2 ± 10.1	3.2 ± 1.2		
	5.299	$\frac{1}{2}^+$	e			
	6.323	$\frac{3}{2}^-$	9.1 ± 2.5	9.1 ± 2.5	7.4	82
	7.155	$\frac{5}{2}^+$	1.0 ± 0.6	1.0 ± 0.6		
	7.301	$\frac{3}{2}^+$	<1.5			
	7.566	$\frac{7}{2}^+$	<2.5			
	8.313	$\frac{1}{2}^+$	<1.2			
	8.576	$\frac{3}{2}^+$	<1.3			
	9.053	$\frac{1}{2}^+$	<0.8			
	9.152	$\frac{3}{2}^-$	<0.6			
	9.155	$(\frac{5}{2})$	<2.8			
	9.225	$\leq\frac{5}{2}$	<1.0			
	9.762	$\frac{5}{2}^-$	<0.8			
	9.829	$\frac{7}{2}$	<3.0			
	9.929	$(\frac{1}{2},\frac{3}{2})^+$	<0.9			
	10.070	$\frac{3}{2}^+$	<1.0			
	10.451	$\frac{3}{2}\rightarrow\frac{7}{2}$	<3.8 [f]			
	10.536	$\frac{5}{2}^{(+)}$	<2.3 [g]			
	10.700	$\frac{3}{2}^+$	e, h			
	10.800	$\frac{3}{2}^{(-)}$	e, i			
^{15}O	5.181	$\frac{1}{2}^+$	e			
	5.242	$\frac{5}{2}^+$	2.9 ± 0.8	1.7 ± 0.9	15.6	
	6.177	$\frac{3}{2}^-$	15.6 ± 3.8	15.6 ± 3.8		91
	6.788	$\frac{3}{2}^+$	<1.9			
	6.859	$\frac{5}{2}^+$	<3.3			
	7.276	$\frac{7}{2}^+$	1.2 ± 0.5	1.2 ± 0.5	1.2	

[a] Nuclear level information from Ref. 5.
[b] α is the cross section for production of a particular state either by direct excitation and/or by γ feeding from higher states.
[c] σ_1 is the result of correcting α for γ feeding from states known to be excited.
[d] σ_2 is the result of correcting σ_1 for γ feeding from states for which only an upper limit is reported.
[e] Conditions did not permit detection of this state.
[f] Unbound: $\Gamma_\gamma/\Gamma \geq 0.85$ (Ref. 4).
[g] Unbound: $\Gamma_\gamma/\Gamma \leq 0.5$ (Ref. 4).
[h] Unbound: $\Gamma_\gamma/\Gamma \leq 0.001$ (Ref. 4).
[i] Unbound: $\Gamma_\gamma/\Gamma = 0.55$ (Ref. 4).

lar state because it may have been augmented by γ feeding from higher states excited too weakly to have measurable values of α. In order to determine the extent of this effect, cross section upper limits for these higher states were calculated by the procedure discussed below. We then subtracted from σ_1 the calculated upper limits multiplied by the appropriate branching ratios. This yields σ_2, an estimate of the cross section for direct excitation of a particular state under the assumption of the largest possible γ feeding and is, consequently, the minimum cross section.

The above analysis assumes that γ decay is not competitive with particle emission for unbound states except for those states whose γ-partial width is known to be a significant fraction of the total width Γ. For the first four unbound states of ^{15}N: $\Gamma_\gamma/\Gamma(10.451) > 0.85$, $\Gamma_\gamma/\Gamma(10.536) < 0.5$, $\Gamma_\gamma/\Gamma(10.700) < 0.001$, and $\Gamma_\gamma/\Gamma(10.800) = 0.55$.[4] Cross section upper limits were determined for the 10.451- and 10.536-MeV levels. No upper limit could be determined for the 10.800-MeV level but it only has a 6% γ branch[5] to the 6.323-MeV state which is the only ^{15}N state with a nonzero value of σ_2. For ^{15}O and ^{14}N, Γ_γ for the first unbound level

TABLE II. Cross sections for π^- reactions on ^{16}O resulting in $(A-2)$ residual nuclei.

Residual nucleus [a] (MeV)		$J^\pi;T$	α [b] (mb)	σ_1 [c] (mb)	σ_2 [d] (mb)	ΔP (MeV/c)
^{14}C	6.093	1^-	e			
	6.589	0^+	e			
	6.728	3^-	1.1 ± 0.5	1.1 ± 0.5	0.6	
	6.901	0^-	1.9 ± 0.5	1.9 ± 0.5	1.9	77
	7.012	2^+	<1.0			
	7.341	2^-	<1.4			
^{14}N	2.313	$0^+;1$	23.4 ± 4.6	7.1 ± 5.6		119
	3.945	$1^+;0$	16.4 ± 3.5	16.4 ± 3.5	15.3	126
	4.913	$(0,1)^-;0$	e			
	5.106	$2^-;0$	2.6 ± 0.8	1.3 ± 1	1.2	
	5.691	$1^-;0$	<6.6			
	5.833	$3^-;0$	1.6 ± 0.6	1.6 ± 0.6	1.6	
	6.198	$1^+;0$	<4.6			
	6.444	$3^+;0$	<1.9			
	7.028	$2^+;0$	<1.7			
	7.966 [f]	$2^{(-)};0$	<1.5			

[a] Nuclear level information from Ref. 5.
[b] α is the cross section for production of a particular state either by direct excitation and/or by γ feeding from higher states.
[c] σ_1 is the result of correcting α for γ feeding from states known to be excited.
[d] σ_2 is the result of correcting σ_1 for γ feeding from states for which only an upper limit is reported.
[e] Conditions did not permit detection of this state.
[f] Unbound.

is not known but the next few unbound levels have negligible values of Γ_γ [5] for decay to bound excited states. Unbound levels of ^{14}C, ^{13}C, and ^{16}N all decay solely by nucleon emission.[5,6] Nuclei such as ^{10}B, ^{12}C, and ^{16}O have many unbound levels for which no values of Γ_γ have been reported, but it is expected that γ feeding from such states would be small.

As noted above, levels decaying with a mean life short enough to result in Doppler broadened spectral peaks yielded nuclear recoil momenta. These were calculated in the usual manner by unfolding the intrinsic line widths from the broadened spectrum peaks and evaluating the expression for $s(\tau_m)$, the slowing down of the recoil nucleus in the target material. A computer program based on the work of Ref. 7 was used for this purpose; results for those levels showing measurable broadening are listed in column 6 of Tables I–III.

The upper limit estimates which were used in estimating the extent of γ feeding from higher levels excited too weakly to have a measurable spectrum peak were based on the following considerations. An examination of all Doppler broadened transitions which were detected indicated that the average momentum transferred to the recoiling nucleus was ~100 MeV/c. This momentum transfer was assumed to be typical and was used with $s(\tau_m)$ computed from reported lifetimes τ_m to estimate a Doppler broadened peak width which was then folded into the system intrinsic width to obtain a maximum linewidth. Using this and the known branching ratios, an estimate was made of the upper limit of the amplitude for this weak level either by inspection or by using a least squares fitting procedure with width and center channel fixed. From this, the cross section was computed in the usual manner. It should be noted that the above cross sections are upper limits and not indicative of probable cross section values.

An estimate was made of the spectrum which would result if the initial pion reaction populated bound levels assuming either (1), equal population of all bound levels or (2), a population proportional

TABLE III. Cross sections for π^- reactions on ^{16}O resulting in residual nuclei other than $(A-1)$ and $(A-2)$.

Residual nucleus [a] (MeV)		$J^\pi;T$	α [b] (mb)	σ_1 [c] (mb)	σ_2 [d] (mb)	ΔP (MeV/c)
^{10}B [f]	0.717	$1^+;0$	9.2 ±1.9	1.7 ±2.5		
	1.740	$0^+;1$	6.5 ±1.5	4.6 ±1.6	4.6	
	2.154	$1^+;0$	3.7 ±1	3.7 ±1	3.1	
	3.585	$2^+;0$	<3			
^{12}C [g]	4.439	$2^+;0$	16.1 ±6.4	16.1 ±6.4	16.1	139
^{13}C [h]	3.086	$\frac{1}{2}^+$	<1.4			
	3.684	$\frac{3}{2}^-$	9.9 ±2.5	7.4 ±2.6	7.4	84
	3.854	$\frac{5}{2}^+$	6.7 ±1.6	6.7 ±1.6	6.7	
^{16}N [h]	0.120	0^-	e			
	0.298	3^-	0.33 ± 0.1	0.30 ± 0.1	0.3	
	0.398	1^-	0.60 ± 0.19	0.60 ± 0.19	0.6	
^{16}O [h]	6.131	$3^-;0$	12.5 ±2.8	12.5 ±2.8	11.2	
	6.919	$2^+;0$	<3			
	7.119	$1^-;0$	e			
	8.872	$2^-;0$	<1.7			

[a] Nuclear level information from Refs. 22–24.

[b] α is the cross section for production of a particular state either by direct excitation and/or by γ feeding from higher states.

[c] σ_1 is the result of correcting α for γ feeding from states known to be excited.

[d] σ_2 is the result of correcting σ_1 for γ feeding from states for which only an upper limit is reported.

[e] Conditions did not permit detection of this state.

[f] ^{10}B cross sections are assumed to be largely due to background contamination.

[g] Cross section corrected for background contamination.

[h] Secondary neutron contamination of these cross sections is possible.

TABLE IV. Comparison of present cross sections with those calculated under the assumption of certain initial population of all bound states.

Residual level		α	(1): Equal initial population of all bound levels [a]	(2): Initial population proportional to $2J_f+1$ [b]
^{15}N	5.270	4.2	19.5	23.3
	6.323	9.1	6.0	5.2
	7.155	1.	6.1	7.1
^{15}O	5.242	2.9	10.8	13.8
	6.177	15.6	3.7	2.8
	7.276	1.2	3.7	5.6
^{14}C	6.728	1.1	4.9	6.1
	6.901	1.9	3.7	0.7
^{14}N	2.313	23.4	14.3	8.2
	3.945	16.4	4.5	3.2
	5.106	2.6	6.8	7.7
	5.833	1.6	3.7	5.6
^{13}C	3.684	9.9	5.0	4.4
	3.854	6.7	3.7	4.3

[a] 1 was calculated by assuming that all bound states of each residual nucleus was equally populated and the known γ branching ratios (Refs. 5, 24) were used to estimate the relative population of lower states following γ feeding from higher states.

[b] 2 was calculated in the same fashion under the assumption of initial population proportional to $2J_f+1$. The normalization is such that the sum of column 3 and column 4 are each equal to the sum of column 2.

to $(2J_f+1)$ where J_f is the spin of the residual level. The known branching ratios are then used to predict the resultant population of each level under each assumption. These results are then compared with the present cross sections without γ feeding corrections (α) in Table IV.

IV. DISCUSSION

A. $(A-1)$ Residual nuclei

Table I lists the cross sections for π^- reactions on ^{16}O which result in excited states of ^{15}O and ^{15}N. The procedure outlined above for subtracting the effects of γ feeding from higher states results in unambiguous excitation of the first $\frac{3}{2}^-$ mirror levels in ^{15}N and ^{15}O and also the 7.276-MeV level in ^{15}O. Our analysis assumes that Γ_γ for states above 10.800 MeV in ^{15}N and 7.552 MeV in ^{15}O is small and thus γ feeding from such states would be negligible.

The γ feeding analysis (Table IV) which assumed certain initial populations of all states of ^{15}N and ^{15}O also indicates that γ decays from higher levels to the $\frac{3}{2}^-$ mirror levels are a small fraction of all decays and thus there is little ambiguity in the cross sections reported for these levels. It should be noted that reported branching ratio measurements[5] for several levels of ^{15}N could not resolve decays to the first and second excited states. In our calculations leading to Table IV, we divided the contributions from such states equally between the ^{15}N 5.271- and 5.299-MeV states.

The strong excitation of the mirror $\frac{3}{2}^-$ states coupled with the relatively small excitation of other states suggests a direct or quasifree reaction mechanism. The configuration of these $\frac{3}{2}^-$ states is predominantly $(p_{3/2})^{-1}$ corresponding to the removal of a single $p_{3/2}$ nucleon from the ^{16}O ground state. If a 20% s-d admixture is included in the ^{16}O ground state wave functions,[8] one obtains the spectroscopic factors: $S(p_{1/2})=1.75$, $S(p_{3/2})=4.00$, $S(d_{5/2})=0.15$, and $S(s_{1/2})=0.07$.

An activation cross section measurement[9] of π^- on ^{16}O resulting in ^{15}O extrapolates to ~38 mb at 230 MeV, the energy of the present experiment. The extrapolation used the shape of the $\pi^-+{}^{12}$C $\to{}^{11}$C excitation function.[9] Although the present γ-ray technique does not detect reactions leading to the ground state of ^{15}O, a quasifree estimate of the total ^{15}O production cross section was made by the following argument: From the above spectroscopic factors, the probability for removal of $p_{1/2}$ neutron leading to the ^{15}O ground state would be ~0.438 times the probability for removal of a $p_{3/2}$ neutron. Assuming reported estimates[10] that the first $\frac{3}{2}^-$ state has 70% of the total $p_{3/2}$ strength, one then arrives at a total $p_{3/2}$ cross section of ~22 mb and hence an expected $p_{1/2}$ cross section of ~10 mb. Since the missing $p_{3/2}$ strength appears in unbound levels and therefore will not contribute to the activation cross section, the measured cross section for the first $\frac{3}{2}^-$ state is added to the expected $p_{1/2}$ cross section and to the cross sections for the other ^{15}O states measured. This results in a total cross section ~30 mb in satisfactory agreement with the activation results.[9]

The first $\frac{5}{2}^+$ mirror levels appear stronger than one would predict on a quasifree basis using the above spectroscopic factors, but γ feeding to these states may be significant. It was not possible to measure a cross section for the first $\frac{1}{2}^+$ mirror states because they are Doppler broadened and lie under the $\frac{5}{2}^+$ γ peaks.

Additional evidence against a quasifree reaction mechanism can be found in the appreciable cross sections for the ^{15}N 7.155-MeV $\frac{5}{2}^+$ state and the ^{15}O 7.276-MeV $\frac{7}{2}^+$ state, and also the relative cross section of the first two $\frac{3}{2}^-$ mirror states. The ratio of cross sections for the latter two states is $\sigma_1(^{15}\mathrm{O})/\sigma_1(^{15}\mathrm{N})=1.7\pm0.4$. Due to the isospin dependence of the πN interaction at the (3, 3) resonance, a direct reaction cross section ratio would be 3 in disagreement with present results. An activation measurement[9] of $\sigma(^{16}\mathrm{O}\xrightarrow{\pi^-}{}^{15}\mathrm{O})/\sigma(^{16}\mathrm{O}\xrightarrow{\pi^+}{}^{15}\mathrm{O})$ ratio was unity also in disagreement with a direct reaction prediction.

Examination of the present results does not point conclusively to any single reaction mechanism. The suggestion[11,12] that π^- scattering may result in excitation of giant resonant states of ^{16}O or ^{16}N followed by nucleon decay may be tested by comparing the present results with a photoexcitation study[13] of the decay scheme of giant resonant state of ^{16}O below 28.7 MeV. These results indicate strong residual excitation of the first $\frac{3}{2}^-$ states in ^{15}N and ^{15}O with the ^{15}N cross section approximately double that of the ^{15}O state. The first $\frac{1}{2}^+$, $\frac{5}{2}^+$ (unresolved), and $\frac{3}{2}^+$ mirror levels were excited to about $\frac{1}{4}$ of the $\frac{3}{2}^-$ excitation in ^{15}N and about $\frac{1}{2}$ of the $\frac{3}{2}^-$ excitation in ^{15}O. Clearly some combination of direct reactions and giant resonant state excitation could account for the present results.

The large measured cross section for states of ^{14}N (Sec. IV B) may indicate that states of $(A-1)$ residual nuclei result from π^- scattering on a nucleon pair or π^- capture in flight. The latter is suggested by the fact that in absorption of stopped π^- on ^{16}O,[14] the only mass 15 level observed was the first $\frac{5}{2}^+$ state in ^{15}N which was relatively strongly excited. This was interpreted as being a π^- quasifree absorption on a p shell np pair leading to a final state with one neutron escaping and the other captured in the $d_{5/2}$ state.

B. $(A-2)$ residual nuclei

Several γ transitions were detected which correspond to residual states in ^{14}N and ^{14}C and thus involve π^- reactions resulting in the removal of two nucleons from the ^{16}O target. The results are reported in Table II. The excitation of the first two excited states of ^{14}N is comparable to that of $(A-1)$ residual nuclei, but our analysis indicates that the observed cross sections for the 2.313-MeV state may be largely if not completely due to γ feeding. It should be noted from Table I that, of the 23.4-mb production of the ^{14}N 2.313-MeV level, 16.3 mb comes from γ feeding, predominately from the 3.945-MeV level.[5] The remaining 7.1 mb could be due to additional feeding from higher bound states particularly the 5.691- and 6.198-MeV levels. The cross sections for the 3.945-, 5.106- and 5.833-MeV levels are unambiguous.

Cross sections for excitation of the first two excited states of ^{14}C could not be determined due to the presence of overlapping peaks. Although no upper limits are given for these states, inspection of the spectrum indicates that any excitation of these states is considerably less than that of the first two excited states of ^{14}N. Excited states of ^{14}O are particle unstable[5] and thus could not be detected in the present experiment.

The relatively large cross sections for two nucleon removal may be evidence of some form of π^- two nucleon pair interaction as proposed by Chivers *et al.*[9] who found evidence that the πNN couple to isospin $T=1$. Unfortunately, the lack of bound excited states of ^{14}O precludes any unique test of the isospin dependence in the present results. Of some interest in this regard is a comparison of the relative excitation of the 0^+, $T=1$ state of ^{14}N at 2.313 MeV and the 1^+, $T=0$ state at the 3.945 MeV. The possible γ feeding makes the cross section for the 2.313-MeV level uncertain; hence, the cross section ratio is $R(0^+/1^+)\leq 0.45$. If the reaction is one step quasifree, the cross section is proportional to the product of the target-residual nucleus spectroscopic factor and a spectroscopic factor for the coupling of the incident pion to the two nucleon pair. The ratio of the former spectroscopic factors for the two states is $S(0^+)/S(1^+)=0.8$.[15] If the πNN coupling is such to produce only a $T_{\pi NN}=1$ state the isospin dependence of the latter spectroscopic factors will then yield the cross section ratio $R(0^+/1^+)=0.45$, a result not in disagreement with the measured value. A πNN interaction coupled primarily to $T=2$ can be ruled out because it would not yield the 1^+, $T=0$ state. πNN coupled to $T=0$ would not involve the 3, 3 resonance.

A comparison of the present results may be made with a similar measurement of γ rays following stopped π^- capture on ^{16}O.[14] This comparison is shown in Table V and indicates a similarity between the two results, especially for mass 14 and lighter nuclei. However, the hypothesis of π^- capture in flight is questionable if one considers the spectra taken in coincidence with the scattering counters surrounding the target. These spectra were generally not useful because of the scintillation counter's inability to identify the outgoing particle, other than the fact that it was charged. π^- capture leading to excited states of ^{14}N would result in the emission of two relatively high energy neutrons which have a less than 10% efficiency for detection in the scintillation counters. Nonabsorptive reactions leading to ^{14}N would produce charged particles even for reactions involving pion charge exchange. The subsequent π^0 decay would result in electrons and positrons in the target and scintillation counters. A comparison between a spectrum taken in coincidence with any of the five scattering counters and a spectrum of γ rays not in coincidence with any of the scattering counters indicated approximately equal excitation of ^{14}N states. In order to make this comparison it was necessary to normalize the ^{14}N peaks in each spectrum to account for the solid angle and efficiency of the five scattering counters. Since reactions producing the ^{16}O 3^- state result uniquely in a single charged pion, the area of the ^{16}O 3^- peak in each spectrum was used to normalize the ^{14}N peaks. The equality of these normalized ^{14}N peaks within statistical errors (~30%) indicate that π^- absorption in flight is not the major contributor to the ^{14}N cross sections.

TABLE V. Comparison of the present results with a similar measurement of stopped π^- capture on ^{16}O (Ref. 14).

Residual level	Transition	$\beta/\beta(^{14}N: \text{II}\to\text{I})$ [a]	$N_\gamma/N(^{14}N: \text{II}\to\text{I})$ [b]
^{14}N 3.945	II→I	1	1
^{14}N 2.313	I→0	1.46	1.25
^{13}C 3.684	II→0	0.62	0.38
^{13}C 3.854	III→0	0.26	0.14
^{14}N 5.106	IV→0	0.13	0.08
^{15}N 5.271	I→0	0.26	0.08
^{14}C 6.728	III→I	0.062	0.018
^{12}C 4.439	I→0	1.01	0.47
^{16}O 6.131	II→0	0.78	0.18

[a] β is the cross section for production of a particular γ-ray transition.
[b] From Ref. 14, N_γ is the number of γ rays detected in a particular transition corrected for efficiency.

C. Residual states of ^{13}C

γ-ray transitions were detected from the 3.684- and 3.854-MeV states of ^{13}C. Because of the high cross section for the (n, α) reaction, it is probable that contamination from secondary neutrons contributed to the ^{13}C cross sections, but we estimate that this contribution is less than 3 mb to each state. This estimate is based on the reported cross sections[16] for the $^{16}O(n, \alpha)$ reaction resulting in excited states of ^{13}C and a calculation of the maximum possible neutron flux induced by pions in the target. All higher energy levels of ^{13}C are unbound,[5] so these cross sections are not ambiguous due to γ feeding.

The present results are in qualitative agreement with calculated spectroscopic factors[17] for quasifree knockout of ^3He from ^{16}O. For the $^{16}O(p, p{}^3He)$ ^{13}C reaction, spectroscopic factors for the 3.684- and 3.854-MeV levels (they are not resolved) are 2.5 times the ground state strength and there is no strength for the 3.086-MeV state.

D. Residual state of ^{12}C and ^{10}B

The largest cross section measured was the broad transition from the first excited state of ^{12}C at 4.439 MeV. The presence of carbon in the scintillation counters surrounding the target makes contamination from inelastic π^- scattering likely. The extent of this contamination was estimated making use of a spectrum of γ rays from π^- on a ^{12}C target. This measurement detected γ rays from the first excited state of ^{11}B and ^{11}C, which were not detected in the present results. The ratio of the upper limits to the ^{11}B and ^{11}C cross sections in the present results to those from the ^{12}C target multiplied by the measured cross section for the 4.439-MeV state from the ^{12}C target yields an estimate of the contamination. The reported cross section of 16.1 mb has been corrected for this contamination. The large apparent cross section for π^- reactions producing $(A-4, Z-2)$ residual nuclei has been subsequently observed with other targets using the present experimental technique.[18,19]

The measured cross sections for the production of states of ^{10}B appear to be largely due to this background contamination. This assumption is compatible with the relative intensities of γ transitions in the spectrum of π^- on ^{12}C.

It should be noted that if the ^{12}C were produced by a quasifree α knockout, the reaction would proceed predominantly to the 4.439-MeV level, the spectroscopic factor for this level being ~5 times that for the ground state.[20]

E. Residual states of ^{16}O and ^{16}N

A cross section of 12.5 ± 2.8 mb was measured for inelastic excitation of the 6.131-MeV 3^- state of ^{16}O. We estimate that the contamination of this cross section due to secondary neutrons would be less than 3 mb.[21] Several states above the particle instability level decay by γ emission,[6] but it is expected that γ feeding to this cross section would be small.

The reported cross sections for reactions resulting in excited states of ^{16}N are small and could be largely due to contamination by secondary neutrons. Our estimate of the maximum contamination by the $^{16}O(n, p)^{16}N$ reaction is of the order of the reported cross sections.

V. CONCLUSION

The present experiment has measured discrete nuclear levels populated by 230-MeV negative pions on ^{16}O. Strong excitation of the first $\frac{3}{2}^-$ states of $(A-1)$ residual nuclei is compatible with a quasifree reaction mechanism, but the ratio of the excitation of this state in ^{15}O to ^{15}N is 1.7 ± 0.4, in disagreement with the quasifree prediction of 3.

Excitation of states of ^{14}N and ^{14}C is similar to stopped π^- capture on ^{16}O reactions but this mechanism is made questionable by spectra accumulated in coincidence with the scintillation counters detecting outgoing particles. A very large cross section was detected for the first excited state of ^{12}C.

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