PHYSICAL REVIEW C VOLUME 17, NUMBER 1 JANUARY 1978

Pion-induced single-nucleon removal to discrete final states*

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(Received 5 August 1977)

γ radiation from targets of ^{7}Li, ^{9}Be, ^{12}C, ^{13}C, and ^{16}O bombarded by π^- and π^+ at energies between 60 and 300 MeV was uniquely associated with states formed by removing a single nucleon by the $(\pi,\pi N)$ reaction. All yields were found to reflect the well-known 3-3 resonance near 180 MeV in the pion-nucleon system. Ratios of yields for π^- and π^+ beams were measured for ^{7}Li, ^{9}Be, and ^{13}C. These ratios were very similar to one another and to previous results on ^{12}C, ^{14}N, and ^{16}O for neutron removal. Several reaction mechanisms based on quasifree processes are tested by comparison to the data, and all are rejected.

[NUCLEAR REACTIONS ^{7}Li, ^{9}Be, ^{12}C, ^{13}C, ^{16}O. $(\pi^{\pm},\pi N)$, detect γ decay of residual nucleus, measure $\sigma(E_\pi)$.]

I. INTRODUCTION

Among the most valuable results from direct reaction analyses with conventional nuclear beams are the single-nucleon parentages of the target nucleus as determined by stripping and pickup reactions. The pion, with its rather different interaction and quantum numbers, could in principle induce reactions revealing new aspects of such single-nucleon parentages. Any such analysis must depend upon a clear understanding of the reaction mechanism by which the nucleon is picked up in a reaction such as $(\pi, \pi N)$. Existing theories for the nucleon removal mechanism range from those based on the impulse approximation for the interaction of a single nucleon with the pion to internuclear cascades among many nuclear interactions with subsequent evaporation of one nucleon. The former approach treats the target nucleon as essentially free, with some modification to account for absorption of the reaction products. This model is analogous to a direct pickup reaction. The latter model is essentially that of a compound nucleus, although the addition of the pion rest mass to the nuclear system provides such excitation that thermal equilibrium would not be anticipated.

A successful direct reaction theory of pion-induced pickup must account for several aspects of the data. The yields to well-known final states must be in proportion to the known spectroscopic factors. The dependence on the pion energy must reflect that seen for the basic pion-nucleon interaction, and finally, the ratio of yields from negative and positive pion beams must reflect the yields known from scattering on a free proton target.

Previous tests of these ideas on light nuclei have been performed by counting the yields of radioactive final nuclei[1-3] or by detecting in-beam γ-ray spectra from complex final nuclei.[4] Both of these approaches have summed the yields to an unknown number of final states, making it impossible to obtain the spectroscopic factors for individual levels. The yields clearly exhibit the pion-nucleon 3-3 resonance near T_π (lab) = 180 MeV, but the ratios of yields by π^- and π^+ have been far from that predicted by the impulse approximation.

In the present work, target nuclei have been chosen to permit the study of neutron or proton removal to individual final states of several isospin values. Neutron removal from ^{7}Li populates the 3.56 MeV 0^+, $T=1$ state of ^{6}Li, the only bound, γ-ray emitting, excited state below $A=7$. Proton removal from ^{9}Be can similarly be studied by the yield of the 0.98 MeV γ ray from the 1^+, $T=1$ state of ^{8}Li. A prominent 4.4 MeV γ ray seen in π^+ bombardment of ^{12}C will be shown to be mainly due to the population of the $\frac{5}{2}^-$, $T=\frac{1}{2}$ states at 4.319 and 4.444 MeV in ^{11}C and ^{11}B, respectively. Neutron removal from ^{13}C provides γ rays only from the 2^+, $T=0$ state at 4.44 MeV and from the 1^+, $T=1$ state at 15.11 MeV in ^{12}C. A previous[3] measurement of the yield of ^{13}N from pion bombardment of ^{14}N also determines the cross section to a unique state, since ^{13}N has no excited states that decay to the ground state. A strong yield to the $\frac{3}{2}^-$ hole states in $A = 15$ is noted from bombardment of ^{16}O.

The incident pion energy was varied for these targets from 60 to 300 MeV (lab), and the energy dependence was found to agree with the known 3-3 resonance. Both π^+ and π^- beams were used with identical geometry to study the ratios of final state yields free of systematic uncertainty. γ-ray data were taken at two angles to detect any dramatic alignment of the final nuclear state.

II. EXPERIMENT

The pion beams were obtained from the EPICS[5] channel of the Clinton P. Anderson Meson Physics Facility of the Los Alamos Scientific Laboratory. A crossed-field velocity selector in the channel eliminated nearly all protons from the π^+ beam. The beam spot is intended as the source for a magnetic spectrometer and was large, about 10 cm wide by 20 cm in the vertical dispersion direction. The flux of minimum ionizing particles through the target was monitored by a plastic scintillator upstream from the target which vetoed protons. For the small ^{13}C target, two such scintillators demanded that the trajectories of the incident particles pass through the target. This direct counting of the pion flux, at instantaneous rates of up to 10^7 π^+/sec, was checked for some runs by a calibrated ion chamber at the beam stop. For the ^9Be and ^{13}C targets, an anticoincidence was demanded from a plastic scintillator downstream from the target. This requires that the exit pion be at some angle other than zero, and reduced chance coincidences in the spectra. The solid angle of this detector was 0.0285 sr. The composition of the beam at the channel energies used has been measured.[6] Typically, at 150 MeV, the beam contains 75% pions, 19% muons, and 4% electrons.

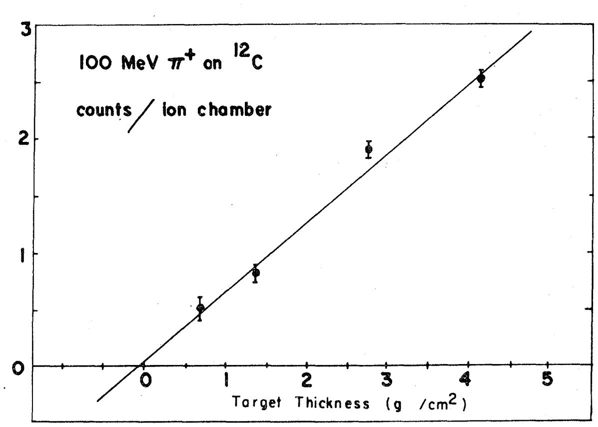

FIG. 1. The yield of the 4.37 MeV γ transition from a natural carbon target bombarded by 100 MeV π^+ is divided by the integrated beam current and plotted against the target thickness. The scale is in arbitrary units. The solid line is a least squares fit, and demonstrates that the yield is linear, not quadratic, in the target thickness. This implies that the γ transition is not due to a sequential process. Targets near 3 g/cm^2 were used for the data analyzed.

The targets were solid sheets of metallic ^7Li (isotopically enriched to 99.99%), a sheet of metallic ^9Be, graphite sheets of natural carbon, and a pressed sheet of amorphous ^{13}C. The ^{13}C target was enriched to $(85 \pm 1)\%$, including the natural carbon in the binding agent. A thin polystyrene case held natural water for the ^{16}O target. Target thicknesses were typically 2 g/cm^2. These thicknesses were varied for ^7Li and natural C between 0.68 and 4.1 g/cm^2 in order to detect sequential processes.[7] The yield was seen to be linear with target thickness over this range, as noted in Fig. 1. This indication of the unimportance of sequential yields for this experiment was verified by explicit calculations with assumed nucleon spectra[8] for the first stage, folded with the known cross section for nucleon-induced reactions.[9] This sequential mechanism provides a yield equivalent to a cross section of less than 1 mb.

γ-ray spectra were simultaneously obtained with 12.7 cm by 12.7 cm NaI(Tl) detectors placed at 90° and 125° with respect to the beam. Fast signals from these detectors were used to measure the time difference between the γ-ray event and the incident pion through the first in-beam scintillator. This time difference information was recorded by an on-line computer together with the energy signal from the detectors. A typical time spectrum, with resolution better than 3 nsec full width at half maximum is shown as Fig. 2. Events in coincidence with the time spectrum off the truly coincident peak were used to measure the accidental target-related spectrum. The detectors were surrounded by 0.64 cm plastic scintillators set to veto particle events from the beam halo or from the target. These veto counters subtended 0.068 sr each as seen from the target, and of course eliminated some real events in which a scattered pion or exciting nucleon encountered the shields. Heavy shielding of lead and boron-loaded paraffin also surrounded the γ-ray detectors except for the entrance aperture. The entire apparatus was situated in the room air.

A valid γ-ray event was thus defined by one (or two) events signaling a pion incident upon the target, (in some cases) the lack of an unscattered pion, the proper time difference between pion and γ ray, and the lack of an event in the detector veto shield. Background spectra were obtained in runs

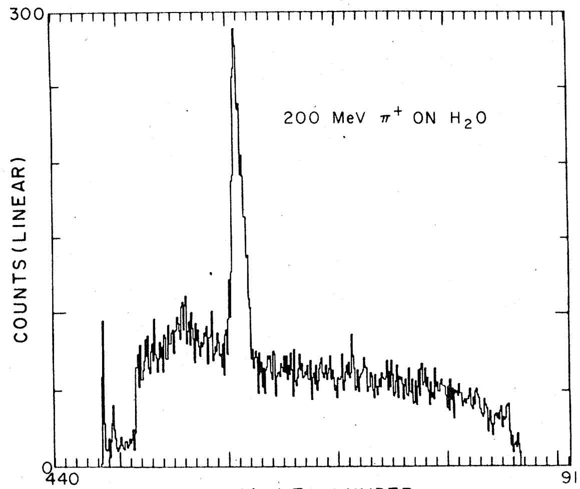

FIG. 2. A spectrum of the time difference between an event in a plastic scintillator upstream from the target and the γ-ray event in the NaI detector. The resolution is better than 3 nsec. A gate on the prompt peak selected the prompt events.

without a target and also be selecting spectra in which the time-of-flight was not correct. Since much of the background was due to the enormous neutron flux from the primary accelerator beam, the latter method was valuable in determining the background.

The NaI(Tl) detectors were equipped with an α particle source for gain stabilization, providing a light peak near that for the 0.98 MeV ^{8}Li line. This α peak could not be fully resolved, but was readily separated from the γ line by appropriate subtraction of events out of true time coincidence.

The detector resolution on a sharp γ-ray line was 7% at 0.66 MeV but for the reaction measurements this was broadened considerably by Doppler effects. A calibrated source of ^{56}Co was used to measure the absolute detector efficiency, which was extrapolated with the aid of standard graphs[10] as far as the 6.1 MeV line from the ^{16}O target. This ^{56}Co source also provided the energy calibration. The efficiency was checked by a Monte Carlo method,[11] which also provided the efficiency calibration for the 15.1 MeV line seen from the ^{13}C target. The uncertainty in these efficiency measurements, and hence in the overall magnitude of the cross sections, was estimated to be ±20%. Since the same efficiency curve was used for all the present data, the uncertainty in the comparison of the results on the several targets is much smaller.

III. RESULTS FOR ^{7}Li

The data for neutron removal from ^{7}Li to the 3.56 MeV 0^+ state of ^{6}Li have already been published,[12] and will only be shown here for comparison to the results for other nuclei. The cross sections for π^+ and for π^- are shown in Fig. 3, as are the ratios of these cross sections. The same results are obtained from the detectors at 90° and 125°. This is to be expected for the isotropic radiation from the 0^+ final state. The curves shown for the cross section points are the free π^+-neutron and π^--neutron cross sections,[13] scaled by 0.10 and 0.05, respectively, for comparison to the data. The prominent peak in the energy dependence is evidently due to the π-N 3-3 resonance. If this resonance dominated the reaction,

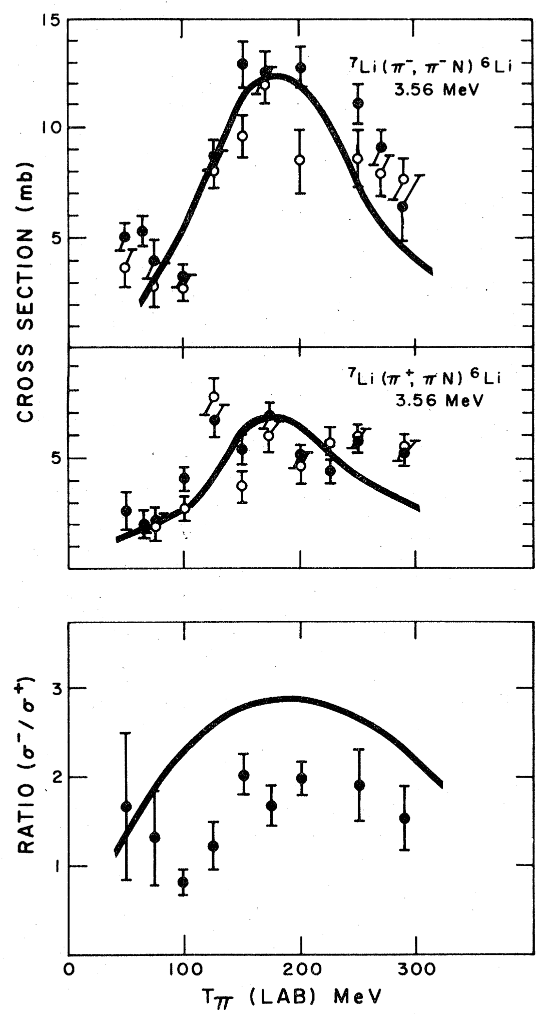

FIG. 3. The cross sections for neutron removal from ^{7}Li to the 3.56 MeV 0^+ state of ^{6}Li are plotted for both π^+ and π^-. The open data points are from the 90° detector, the solid points from the 125° detector. The curves are the free π-nucleon total cross sections, scaled to compare to the magnitude of the ^{7}Li data. The ratios of the π^- to π^+ yields are also plotted compared with the ratio of the free π-nucleon data.

the ratio of π^-- to π^+-induced neutron removal would be 3 near 180 MeV in a strict quasifree model. The observed ratio of π^- to π^+ total cross section on free neutrons is compared with the data, which exhibit a ratio near 1.9, not 3.

IV. RESULTS FOR ^{9}Be

The only proton removal measurement to a discrete final state reported to date from a light nucleus is from the present yield to the 0.981 MeV ^{8}Li line from bombardment of ^{9}Be. This 1^+, $T=1$ state is the only γ-ray emitting level of ^{8}Li, and there are no other γ rays near this energy from nuclei with $A \leq 9$. Hence the γ-ray signature is unique. A sample spectrum, after subtraction of accidental coincidences, is shown as Fig. 4. The cross sections are shown as Fig. 5, as are the ratios of π^+- to π^--induced proton removal. The curves are again the results of free pion-nucleon measurements, scaled by 0.25 for the π^- and 0.067 for the π^+. Although data were taken at fewer pion energies than for ^{7}Li, the 3-3 resonance is noted clearly. For the π^- data at 120 MeV, there is an evident discrepancy in the yields observed at the two angles, plotted as open and closed circles. This could be evidence for the alignment of the 1^+ γ emitting state, which could provide a γ-ray angular distribution of order $P_2(\cos\theta)$ as well as a larger isotropic term. The detector at 125° (the closed points) was at the zero of $P_2(\cos\theta)$.

The ratio of yields shows a discrepancy from the impulse approximation prediction even greater than was seen for ^{7}Li. All the results from the

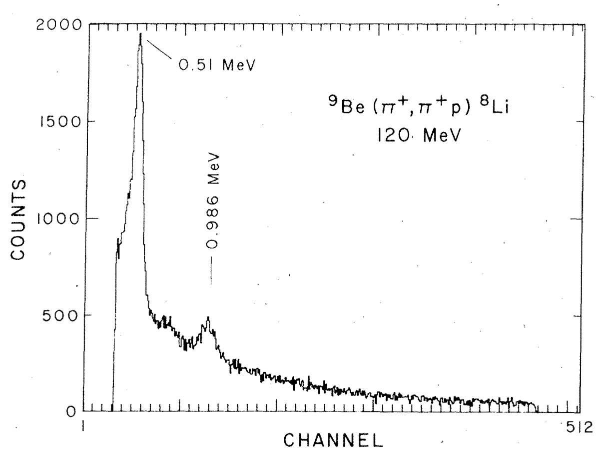

FIG. 4. A spectrum from π^+ bombardment of ^{9}Be at 120 MeV. The decay of the 1^+ state at 0.986 MeV in ^{8}Li provides the peak seen. A background subtraction has been used from the off-time coincidence spectrum, as in Fig. 2.

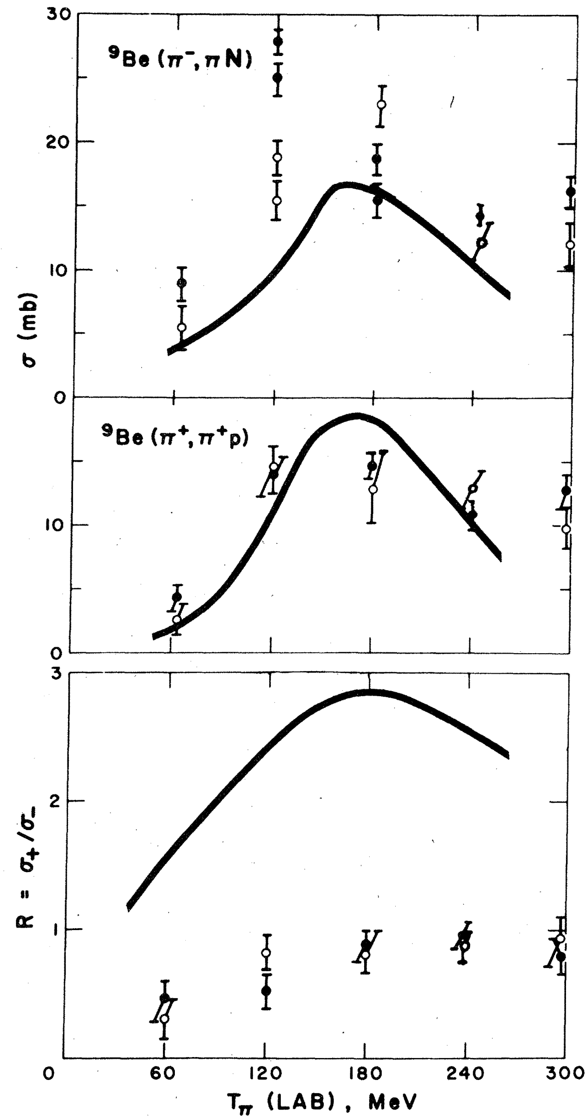

FIG. 5. The cross sections and ratios of cross sections for pion-induced proton removal to the 0.986 MeV state of ^{8}Li are shown, as in Fig. 3. The free π-nucleon data are scaled for better comparison to the data.

several targets will be compared more fully in Sec. VIII.

V. RESULTS FOR ^{12}C

The spectrum shown in Fig. 6 was observed with 225 MeV π^+ bombardment of natural carbon. Only one prominent photopeak is noted other than the 2.22 MeV γ ray from the $n+p$ reaction. The best calibration of the energy at the lowest beam energy provides 4.37 ± 0.05 MeV, based on the 4.44 MeV line from a PuBe neutron source. This calibration at $T_\pi = 64$ MeV is expected to have the least Doppler broadening. The cross section for this transition is plotted in Fig. 7, again compared with the free π^+-proton data, scaled by 0.17 to provide the solid curve. A previous experiment[14] at $T_{\pi^+}=73$ MeV measured an absolute yield of a γ line near 4.4 MeV to be 14.5 ± 3.0 mb at 90°, in exact agreement with the present results. A 4.44 MeV line was seen strongly in an experiment with a Ge(Li) detector, but is not easily assigned due to the use of a very thick carbon target.[15]

One first expectation is that this γ transition is due to the inelastic scattering to the very collective 2^+ state of ^{12}C at 4.44 MeV. Fortunately, the inelastic negative pion scattering to this state has been explicitly measured by Binon *et al.*[16] at a number of beam energies. No difference between π^+ and π^- data is expected for this purely isoscalar transition. Also, no appreciable γ decay from higher states to the 2^+ state enhances the γ-ray yield over the inelastic scattering yield.[17]

It has been found that collective distorted-wave Born approximation (DWBA) predictions using optical model parameters that provide good fits to the elastic pion data also provide good fits to the inelastic data with a deformation parameter $|\beta| = 0.56$,[18] very near that known from other scattering measurements. The total inelastic cross section to this 2^+ state may thus be calculated reliably in the DWBA with the code DWPI.[19] The data of Binon[16] go to large enough angles that it is known that no surprising, very large cross section is seen at back angles. More recent data con-

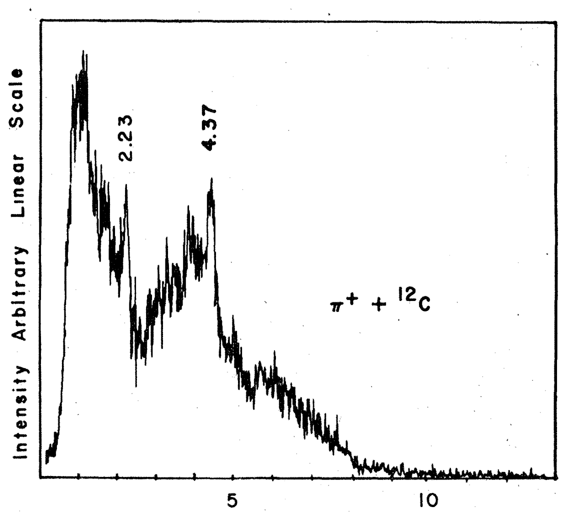

FIG. 6. A spectrum obtained from 180 MeV π^+ bombardment of a natural carbon target. The 2.23 MeV line is primarily from neutron capture on hydrogen. The best calibration provides 4.37 ± 0.04 MeV for the prominent peak.

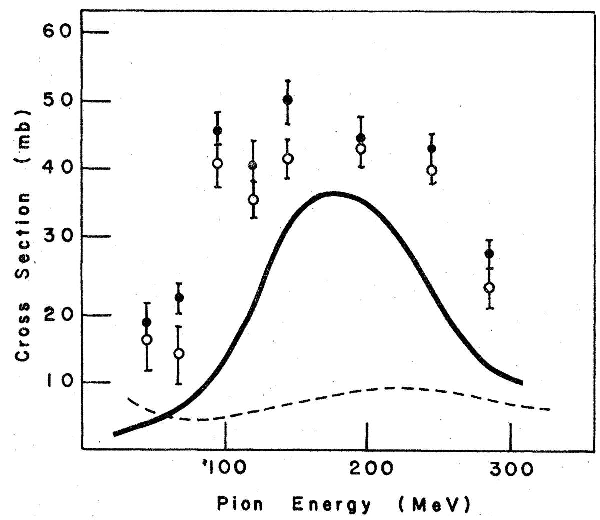

FIG. 7. The yield of 4.37 MeV γ radiation from π^+ bombardment of carbon is plotted as in Fig. 3. The isoscalar average of free pion-nucleon scattering provides the solid curve, scaled to compare with the present data. The broken curve is the prediction for inelastic scattering to the collective 2^+ state of ^{12}C at 4.44 MeV, as discussed in the text.

firm the quality of the DWBA predictions at 150 MeV out to angles of 140°.[20] At 50 MeV, the standard DWBA prediction, as followed here, underestimates the data by about a factor of 2.[21] The DWPI predictions are plotted as the broken curve in Fig. 7. At 50 MeV, the more recent data of Ref. 21 would raise the prediction by about a factor of 2.

On the resonance, no more than one-fifth of the 4.37 MeV γ-ray yield is due to the inelastic scattering and the γ-ray data and DWBA calculation show an energy dependence of rather different shape. This DWBA prediction for the energy dependence of a direct reaction is much as found or predicted for other pion scattering or charge-exchange data.[22] The flat curve is due to the increased nuclear absorption of the pion near the 3-3 resonance suppressing, in part, the increasing strength of the interaction on that resonance.

Since the evidence is that the observed γ ray is largely not due to the inelastic scattering, nor from the small ^{13}C content of the target (see Sec. VI), the transition must be in ^{11}B or ^{11}C.[17] No such high energy transition is possible for nuclei with $A \leq 10$. The levels of these $A = 11$ mirror nuclei are such that with the Doppler broadened peak it would be difficult to distinguish the final nucleus. A γ ray as measured at 4.37 ± 0.05 MeV may be obtained from either the decay of the $\frac{5}{2}^-$ 4.445 MeV state of ^{11}B or the $\frac{5}{2}^-$ 4.319 MeV state of ^{11}C. The only higher bound states that decay to these are at 6.743 MeV in ^{11}B and 6.48 MeV in ^{11}C, and with the known[17] branching ratios for these decays, any feeding to the 4.4 MeV states would be accompanied by a 3.30 MeV transition. The limit on this transition is about one-seventh of the intensity of the 4.37 MeV γ ray, indicating that not more than 15% of the 4.4 MeV decay of the $\frac{5}{2}^-$ states is due to such feeding. Therefore, primarily a single final excited state is populated by single-nucleon removal. Of course, any population of the ground state is undetected.

These results may be compared directly with the production of ^{11}C, as detected by the residual radioactivity.[2] The peak strength near 180 MeV to the $\frac{5}{2}^-$ states is 36 mb for π^+ (see Fig. 7), after the small correction is made for inelastic scattering. This is compared with 70 mb for π^- and 45 mb for π^+ for populating all bound states of ^{11}C.[2] Using charge symmetry, the present work and the data of Ref. 2 lead to the inference that 28% of the neutron removal from ^{12}C goes to the $\frac{5}{2}^-$ state of ^{11}C, 62% to the $\frac{3}{2}^-$ ground state, and about 10% to other bound states where limits on the γ-ray intensities may be placed from the spectra such as Fig. 6. The only states that are not so checked for are the $\frac{1}{2}^-$ states in mass 11 near 2 MeV, since their decay radiation would not be resolved from the intense 2.2 MeV background line. With the weighting of neutrons and protons as determined from isospin invariance and using the ^{11}C experiment, the weighted average γ-ray energy should be 4.40 MeV, in good agreement with the measured value of 4.37 ± 0.04 MeV.

This strong population of $\frac{5}{2}^-$ final states is not at all as observed in a purely direct reaction measurement such as ^{12}C$(p,d)^{11}$C,[23] where only the $\frac{3}{2}^-$ ground state is strongly excited. A larger yield to the $\frac{5}{2}^-$ state of ^{11}C is seen in the ^{12}C(^{3}He, α)^{11}C experiment,[24] and is interpreted as due to two-step excitation through the collective states. The $\frac{7}{2}^-$ state of ^{11}C at 6.48 MeV is seen strongly due to the same mechanism, but the lack of the γ-ray signature for that state in the present experiment indicates that this state is not strongly populated by the pion reactions.

A prominent direct interaction of the pion with a complex nucleus is the quasideuteron absorption, ^{12}C$(\pi^+, 2p)^{10}$B. The yield of prompt γ rays from the known[25] states of ^{10}B indicates a cross section for the 4^+ state at 6.03 MeV not greater than 4 mb. The yields to the first excited states of ^{10}C and ^{10}Be, which are too near to resolve, are not greater than 10 mb. These numbers are consistent with the cross sections reported by radioactivity experiments[1] that sum over all final bound states and with experiments directly observing the two protons.[26] A γ transition from the 3.59 MeV state of ^{10}B is noted, and will be reported elsewhere.[27] It is further known that (π^+, p) reactions have very small cross sections[28] and would not affect the present conclusions.

VI. RESULTS FOR ^{13}C

Neutron removal from ^{13}C will provide two γ rays from ^{12}C, without complication of feeding from other levels. The spectrum in Fig. 8 shows the 4.44 MeV line from the 2^+, $T = 0$ state and the 15.11 MeV peak from the 1^+, $T = 1$ state. The 15% ^{12}C content of the target provides 16% of the 4.4 MeV peak, using the cross sections of the previous section. The cross sections for the two transitions in ^{12}C are shown in Figs. 9 and 10, as are the ratios of π^- to π^+ yields. Proton removal to ^{12}B cannot provide γ rays of energy greater than 3.3 MeV. No γ radiation is expected from ^{9}Be as populated by α particle removal from ^{13}C. Two-nucleon removal to the $\frac{5}{2}^-$ states in $A = 11$ could provide γ radiation contamination of the 4.4 MeV peak, but as indicated in the previous section, this two-nucleon cross section is not greater than a few mb.

The ^{13}C data also indicate that inelastic scattering is not responsible for the γ rays noted. The 3.684 MeV state of ^{13}C was populated at about one-third the strength of the ^{12}C 4.44 MeV 2^+ state in an α particle scattering experiment.[29] The pion-induced γ-ray spectrum at Fig. 8 indicates that not more than 2 mb is allowed for the 3.68 MeV decay, while 15 mb would be expected if the 4.4 MeV γ peak seen from the ^{12}C target were due to inelastic scattering. This is further evidence in support of the arguments of Sec. V.

The cross sections to the 2^+ state are nearly a factor of 6 larger than those to the 1^+ state, but both show the characteristic resonance. The ratios of π^-- to π^+-induced yields are somewhat

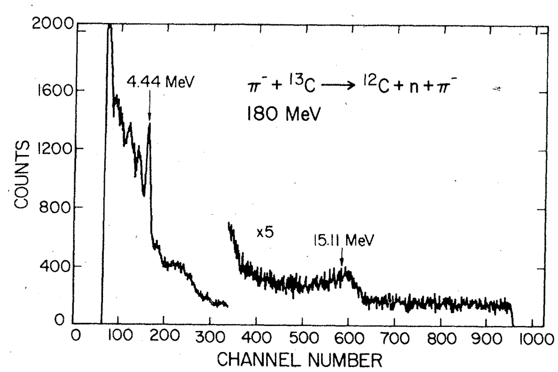

FIG. 8. A spectrum from π^+ bombardment of an enriched ^{13}C target. Prominent lines from the decay of the 4.44 and 15.1 MeV states in ^{12}C are noted.

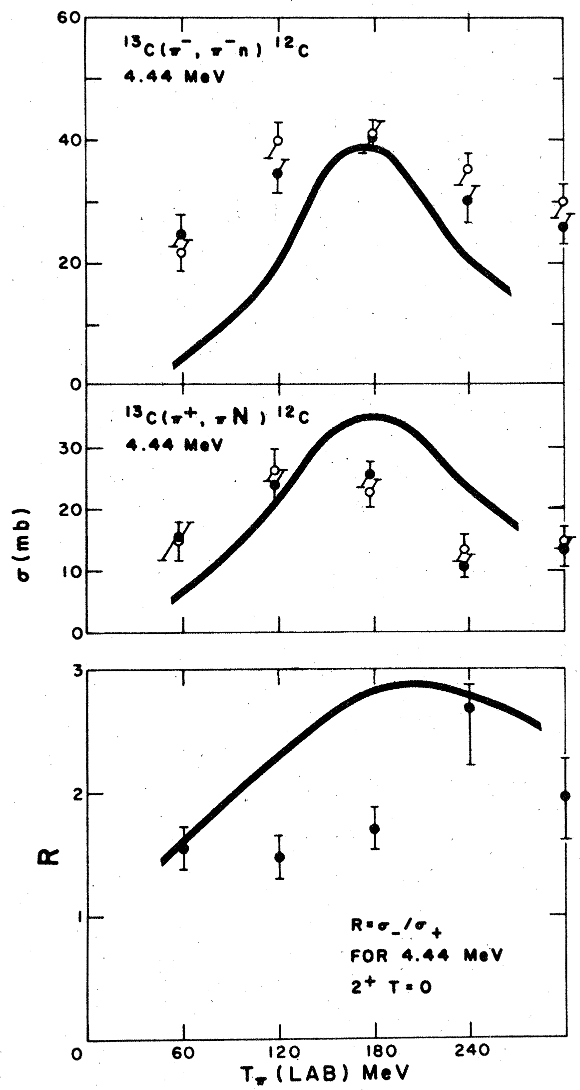

FIG. 9. The yields of 4.4 MeV γ radiation from pion bombardment of ^{13}C are plotted as in Fig. 3. The bottom section shows the ratio of these cross sections. Again, the solid curves are scaled from the free pion-nucleon data.

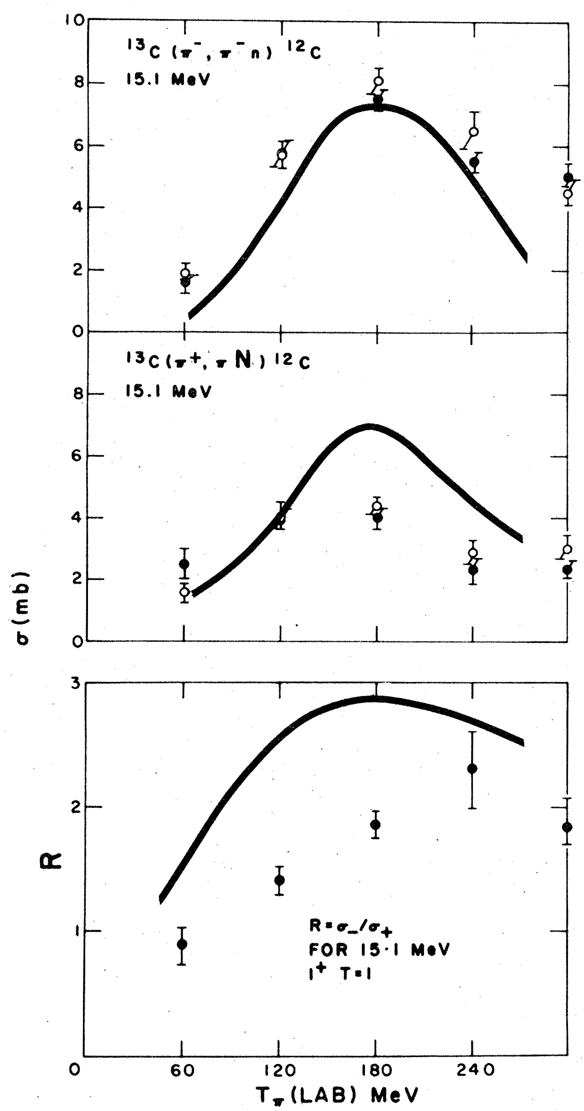

FIG. 10. The cross sections and ratios of cross sections for 15.1 MeV γ radiation from pion bombardment of ^{13}C are shown, as in Fig. 3. These yields are about a factor of 6 smaller than were found for the 4.4 MeV state.

higher than was the case for ^7Li and ^9Be, but are very similar for the two final states of ^{12}C.

VII. RESULTS FOR ^{16}O

Two prominent photopeaks are seen in the spectrum from π^+ bombardment of a water target as shown in Fig. 11. High resolution Ge(Li) spectra from π^+ bombardment of ^{16}O show[4] that three lines are found near 6.2 MeV. The transitions, and their approximate relative strengths, are from the 6.131 MeV 3^- state of ^{16}O (25%), populated by isoscalar inelastic scattering, from the 6.177 MeV $\frac{3}{2}^-$ state of ^{15}O (27%) and from the 6.323 MeV $\frac{3}{2}^-$ state of ^{15}N (48%). As discussed in Ref. 4, no significant feeding of the $A=15$ lines is obtained from higher states. Several states in ^{16}O have significant branches to the 6.131 MeV 3^- state, and the strong transition observed is not unexpected. The strong 4.4 MeV line is due to α particle removal from ^{16}O to the lowest 2^+ state of ^{12}C, and is not discussed here.[27]

The cross sections for the population of the 6.2 MeV transition are shown in Fig. 12. The absolute magnitude near 180 MeV agrees with the work of Ref. 4 to within ±25%. The target for the present

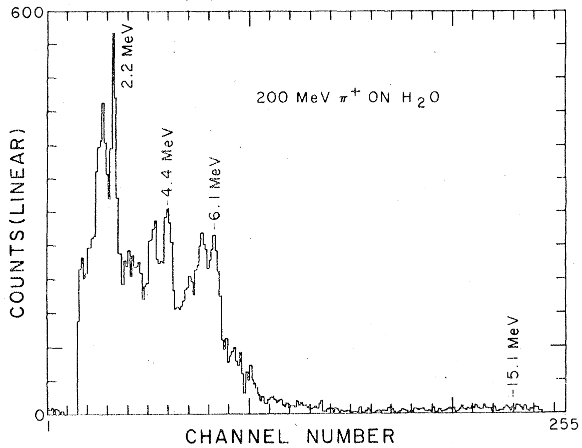

FIG. 11. A spectrum from bombardment of a water target by 225 MeV π^+. The contribution from the empty box has been subtracted. The 4.4 MeV line is from four-nucleon removal from ^{16}O, and the 6.1 MeV line is from single-nucleon removal to the $\frac{3}{2}^-$ states in $A = 15$.

experiment is thinner by a factor of 8 than that used in Ref. 4, and inelastic scattering to the ^{16}O 3^- state by nucleons produced in the target is expected to be less important.

VIII. DISCUSSION OF QUASIFREE REACTION MECHANISMS

The first comparison will be that of the $(\pi, \pi N)$ cross sections to spectroscopic factors found from direct nuclear reactions. The $(\pi, \pi N)$ yields are those near 180 MeV, taking the π^- result for neutron removal and the π^+ result for proton removal.

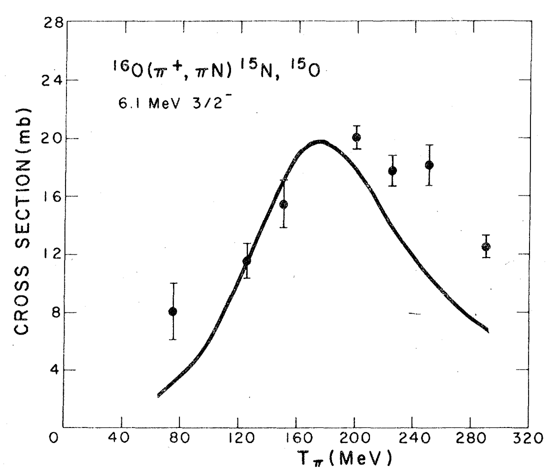

FIG. 12. The 90° yield for single-nucleon removal by π^+ from ^{16}O is plotted against the pion lab energy. The solid curve is the isoscalar sum of pion-nucleon cross sections, scaled by dividing by 14 to compare with the data. The prominent 3-3 resonance has appeared in all the one-nucleon-removal cross sections.

About 61%, as discussed in Secs. V and VIII, of the $A = 11$ and $A = 15$ unresolved γ-ray yields are ascribed to the proton removal by positive pions. Since the final nucleus has only one bound state, the radioactive decay of ^{13}N from π^- bombardment of ^{14}N may also be included.[3] In the comparison of Table I it is seen that no single scaling factor converts the cross sections from $(\pi, \pi N)$ to the known spectroscopic factors.

The simple impulse approximation treats each pion-nucleon collision as essentially that for free pion-nucleon scattering. In this limit, the ratio of π^-- to π^+-induced neutron removal is simply 3 on the 3-3 resonance and in general may be predicted from the free pion scattering.[13] This ratio is compared with the observed ratios for the four final states investigated by both π^+ and π^- in Figs. 3, 5, 9, and 10. Neither the magnitude nor energy dependence are as predicted in this model.

If nuclear absorption effects are simply included by allowing the exiting nucleon to charge exchange, the simple ratio of 3 on the resonance is considerably modified.[30,31] A probability $P = 0.25$ for this predicts ratios equal to 2.0 for ^6Li, 1.16 for ^8Li, and 1.56 for both ^{12}C $(T = 0)$ and ^{12}C $(T = 1)$. Only the valence $p_{3/2}$ nucleons are included in this calculation. These predictions compare reasonably well with the observed values of 1.7 ± 0.2, 0.85 ± 0.10, 1.7 ± 0.2, and 2.0 ± 0.2, respectively. The analog charge exchange probability for the three $T = 1$ final states should be large, and perhaps the

TABLE I. The pion-induced nucleon removal cross sections near 180 MeV pion energy are compared with the spectroscopic factors from light-ion-induced reactions. For neutron removal, the π^- yield is listed, while the π^+ yield is listed for proton removal.

Final state	$(\pi, \pi N)$ Yield (mb)	Spectroscopic factor
$^6Li(0^+, T=1)$	12	1.0 [a]
$^8Li(1^+, T=1)$	15	0.63 [b]
$^{11}C(\frac{5}{2}^-, T=\frac{1}{2})$	12	0.0005 [c]
$^{12}C(2^+, T=0)$	42	1.2 [d]
$^{12}C(1^+, T=1)$	8.3	1.0 [d]
$^{13}N(\frac{1}{2}^-, T=\frac{1}{2})$	15 [e]	0.7 [f]
$^{15}O(\frac{3}{2}^-, T=\frac{1}{2})$	16 [g]	2.6 [h]
$^{15}N(\frac{3}{2}^-, T=\frac{1}{2})$	17 [g]	3.7 [i]

[a] Reference 33.
[b] Reference 34.
[c] Reference 35.
[d] Reference 36.
[e] Reference 3.
[f] Reference 37.
[g] Reference 4.
[h] Reference 38.
[i] Reference 39.

same. For the ^{12}C ($T=0$) state, however, no analog charge exchange is possible, and the probability P should be much smaller. The ratios seen in Figs. 9 and 10 are found to be identical, and hence the present result for the two transitions seen in π^- and π^+ bombardment of ^{13}C precludes the validity of the simplest modification to the impulse approximation. Other evidence against this simple model has been reported.[32]

If the π-nucleon system in the nucleus forms an explicit Δ state ($J=\frac{3}{2}$, $T=\frac{3}{2}$), this excited nucleon could also charge exchange before exiting or decaying back to a nucleon plus a pion. The reaction channels and their relative weights with the assumed $T=\frac{3}{2}$ state are listed in Table II. The ratio of π^- to π^+ yields is then calculated as in Ref. 30, providing the expressions in Table II for each state. Only the nucleons in the $p_{3/2}$ shell are counted to provide the values for N' and Z'.

Note that for ^{6}Li the ratio is predicted to be 3 for any value of P. For $P=0.25$, the results for ^{8}Li and ^{12}C are 1.40 and 2.15, compared with the observed values 0.85 ± 0.10 and 1.7 ± 0.2. This model for the explicit formation of the excited nucleon state must be discarded due to the clash with the observed ratio of 1.7 ± 0.2 for the 3.56 MeV transition in ^{6}Li. As noted in Table II, the expressions obtained for final states in ^{8}Li and ^{12}C are not appreciably different from those obtained in the nucleon charge exchange model, and these data constitute no test of the model. Table III compares the nucleon and Δ charge exchange models for a ^{12}C traget.

TABLE II. For pion-induced nucleon removal through formation and decay of an explicit excited nucleon in the $T=\frac{3}{2}$ state, that excited nucleon may charge exchange to change the ratio of π^-- to π^+-induced yields from that expected in the quasifree model. The ratio is found by the reaction channels listed, with the weights determined by the isospin Clebsch-Gordan coefficients. For three targets, the complete ratios are listed.

$$^{7}\mathrm{Li}+\pi^+\rightarrow{}^{6}\mathrm{Li}+\Delta^+(3)\rightarrow{}^{6}\mathrm{He}+\Delta^{++}(1)$$
$$^{7}\mathrm{Li}+\pi^+\rightarrow{}^{6}\mathrm{Li}+\Delta^+(3)\rightarrow{}^{6}\mathrm{Be}+\Delta^{0}(\tfrac{4}{3})$$
$$^{7}\mathrm{Li}+\pi^+\rightarrow{}^{6}\mathrm{He}+\Delta^{++}(9)\rightarrow{}^{6}\mathrm{Li}+\Delta^{+}(1)$$

$$^{7}\mathrm{Li}+\pi^-\rightarrow{}^{6}\mathrm{Li}+\Delta^-(9)\rightarrow{}^{6}\mathrm{He}+\Delta^{0}(1)$$
$$^{7}\mathrm{Li}+\pi^-\rightarrow{}^{6}\mathrm{He}+\Delta^0(3)\rightarrow{}^{6}\mathrm{Li}+\Delta^{-}(1)$$

$$R=\sigma_-/\sigma_+=\frac{9N'(1-P)+3Z'P}{3N'(1-P-\frac{4}{3}P)+9Z'P}=3\quad\text{for } {}^{6}\mathrm{Li}$$

$$R=\sigma_+/\sigma_-=\frac{9Z'(1-P)+3N'P}{3Z'(1-P)+9N'P}=\frac{6-3P}{2+7P}\quad\text{for } {}^{8}\mathrm{Li}$$

$$R=\sigma_-/\sigma_+=\frac{9N'(1-P)+3Z'P}{3N'(1-\frac{7}{3}P)+9Z'P}=\frac{45-33P}{15+P}\quad\text{for } {}^{12}\mathrm{C}$$

TABLE III. The two charge exchange ratios for ^{11}C production by π^- and π^+ are given. The reaction channels for the charge exchange of the excited nucleon are given as Table II.

$$^{12}\mathrm{C}+\pi^+\rightarrow{}^{11}\mathrm{B}+\Delta^{++}(9)\rightarrow{}^{11}\mathrm{C}+\Delta^{+}(1)$$
$$^{12}\mathrm{C}+\pi^+\rightarrow{}^{11}\mathrm{C}+\Delta^{+}(3)\rightarrow{}^{11}\mathrm{B}+\Delta^{++}(1)$$
$$^{12}\mathrm{C}+\pi^-\rightarrow{}^{11}\mathrm{B}+\Delta^{0}(3)\rightarrow{}^{11}\mathrm{C}+\Delta^{-}(1)$$
$$^{12}\mathrm{C}+\pi^-\rightarrow{}^{11}\mathrm{C}+\Delta^{-}(9)\rightarrow{}^{11}\mathrm{B}+\Delta^{0}(1)$$

$$R=\sigma_-/\sigma_+=\frac{9Z'(1-P)+3N'P}{3N'(1-P)+9Z'P}=\frac{9-6P}{3+6P}\quad\text{for } {}^{11}\mathrm{C}$$

by nucleon charge exchange (Ref. 30),

$$R=\frac{9-8P}{3+6P}\quad\text{for } {}^{11}\mathrm{C}$$

Another direct reaction model would assume the pickup of a nucleon by the incident pion to form an explicit Δ particle which then decays outside the nucleus to provide the exiting nucleon and pion. Any such mechanism must predict yields to final state in proportion to the single-nucleon parentage as measured by pickup spectroscopic factors. Even if the quantum numbers of the picked up nucleon change in the interaction, the final state is still the simple one-hole state, and this is the state detected by its γ radiation. No such simple relation is seen from Table I.

When genuine quasifree kinematics between the pion and proton in the final state are demanded the ratio of π^+ to π^- proton production yields on targets of ^{27}Al and ^{208}Pb are about 7.2 and 6.5, respectively,[40] quite near the value of 9 expected in the simplest impulse approximation. This result implies that charge exchange modifications for truly quasifree reactions are not large,[41] and suggests that the present results are not due to a simple mechanism such as quasifree scattering. It is also noted that the large cross sections for pion-induced single nucleon removal are nearly 10% of the pion reaction cross section on these targets at the 3-3 resonance.[42] This suggests some collective or coherent reaction mechanism involving the entire nucleus, not just one nucleon.

Indeed, γ spectra from pion bombardment of ^{62,64}Ni show large yields for nucleon removal, with a spectrum much as predicted by a model similar to that of a compound nucleus. The ratio of the yields for π^-- and π^+-induced reactions is essentially unity.[43]

IX. CONCLUSION

A systematic study of pion-induced removal to discrete final states in light nuclei has shown several general trends. First, the pion-nucleon resonance near 180 MeV is reflected in all the yields. This energy dependence is more striking than is noted for inelastic scattering or pion charge exchange cross sections. Second, the ratio of π^-- to π^+-induced neutron removal (or of π^+- to π^--induced proton removal) is about half that predicted by a quasifree scattering mechanism, and displays an energy dependence unlike these predictions. Third, the cross sections are as large as 10% of the total reaction cross sections—this to one particular final nuclear level.

These data are sufficient to thoroughly eliminate the models for pion-induced nucleon removal by the quasifree interaction of the pion with individual bound nucleons.

ACKNOWLEDGMENTS

Special thanks are due Dr. H. A. Thiessen for the excellent performance of the EPICS channel. We wish to thank N. DiGiacomo, J. McGill, and J. Whitenton for help in the data runs. Extensive discussions with Dr. E. S. Rost were most useful in clarifying several concepts.

*Supported in part by the U. S. Energy Research and Development Administration and the Robert A. Welch Foundation.

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[1]D. T. Chivers *et al.*, Phys. Lett. 26B, 574 (1968); Nucl. Phys. A126, 129 (1969).

[2]B. J. Dropesky *et al.*, Phys. Rev. Lett. 34, 821 (1975); L. H. Batist *et al.*, Nucl. Phys. A154, 480 (1975).

[3]N. P. Jacob and S. S. Markowitz, Phys. Rev. C 13, 754 (1976).

[4]B. J. Lieb *et al.*, Phys. Rev. Lett. 34, 965 (1975); B. J. Lieb and H. O. Funsten, Phys. Rev. C 10, 1753 (1974).

[5]D. C. Slater *et al.*, Bull. Am. Phys. Soc. 21, 610 (1976); LAMPF Users Manual (unpublished).

[6]H. A. Thiessen *et al.*, Los Alamos Informal Report No. LA-6663-MS, 1977 (unpublished).

[7]R. A. J. Riddle *et al.*, Nucl. Phys. A260, 349 (1976).

[8]M. E. Bellotti, D. Caballi, and C. Matteuzi, Nuovo Cimento A18, 75 (1973); J. F. Amann *et al.*, Phys. Rev. Lett. 35, 1066 (1976); H. J. Ziock *et al.*, Bull Am. Phys. Soc. 22, 526 (1977).

[9]D. W. Devins *et al.*, Nucl. Phys. A126, 261 (1969); F. Ajzenberg-Selove, Nucl. Phys. A268, 40 (1976); J. B. Swint, A. C. L. Barnard, T. B. Clegg, and J. L. Weil, Nucl. Phys. 86, 119 (1966).

[10]J. B. Marion and F. C. Young, *Nuclear Reaction Analysis, Graphs and Tables* (Wiley, New York, 1968).

[11]M. Giannini, P. R. Oliva, and M. C. Ramorino, Nucl. Instrum. Methods 81, 104 (1970); K. Boyer (private communication).

[12]J. E. Bolger *et al.*, Phys. Rev. Lett. 37, 1206 (1976).

[13]R. J. Cence, *Pion Nucleon Scattering* (Princeton U.P., Princeton, 1969); A. A. Carter *et al.*, Nucl. Phys. B26, 445 (1971).

[14]H. Hilscher, W.-D. Krebs, G. Sepp, and V. Soergel, Nucl. Phys. A158, 593 (1970).

[15]J. Lieb and H. Funsten, in *High Energy Physics and Nuclear Structure*, edited by S. Devons (Plenum, New York, 1970).

[16]F. Binon *et al.*, Nucl. Phys. B17, 168 (1970).

[17]F. Ajzenberg-Selove, Nucl. Phys. A248, 1 (1975).

[18]G. Edwards and E. S. Rost, Phys. Rev. Lett. 785 (1971).

[19]R. A. Eisenstein and G. A. Miller, Comput. Phys. Commun. 8, 130 (1970).

[20]J. Piffaretti *et al.*, Phys. Lett. 67B, 289 (1977).

[21]S. A. Dytman *et al.*, Phys. Rev. Lett. 38, 1059 (1977).

[22]Y. Shamai *et al.*, Phys. Rev. Lett. 36, 82 (1976); D. A. Sparrow, Phys. Lett. 58B, 309 (1975).

[23]H. G. Pugh, D. L. Hendrie, M. Chabre, and E. Boschitz, Phys. Rev. Lett. 14, 434 (1965).

[24]R. N. Singh *et al.*, Nucl. Phys. A205, 97 (1973).

[25]F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. A227, 1 (1974).

[26]J. Favier *et al.*, Phys. Lett. 25B, 409 (1967).

[27]G. R. Smith *et al.*, Phys. Lett. (to be published).

[28]J. Amato *et al.*, Phys. Rev. C 9, 501 (1974).

[29]B. G. Harvey *et al.*, Phys. Rev. 146, 712 (1966).

[30]M. M. Sternheim and R. R. Silbar, Phys. Rev. Lett. 34, 824 (1975).

[31]R. R. Silbar, J. N. Ginocchio, and M. M. Sternheim, Phys. Rev. C 15, 371 (1977); R. R. Silbar, *ibid.* 15, 1158 (1977).

[32]P. J. Karol, Phys. Rev. Lett. 36, 338 (1976).

[33]L. A. Kull, Phys. Rev. 163, 1066 (1967).

[34]U. Schwinn *et al.*, Z. Phys. A275, 241 (1975).

[35]S. Cohen and D. Kurath, Nucl. Phys. A141, 145 (1970).

[36]D. K. Scott *et al.*, Nucl. Phys. A141, 497 (1970).

[37]R. L. Kozub, L. A. Kull, and E. Kashy, Nucl. Phys. A99, 540 (1967).

[38]J. L. Snelgrove and E. Kashy, Phys. Rev. 187, 1246 (1969).

[39]H. C. Hiebert, E. Newman, and R. H. Bessel, Phys. Rev. 154, 898 (1967).

[40]T. Sharma *et al.*, Bull. Am. Phys. Soc. 21, 1295 (1976); L. W. Swenson *et al.* (unpublished).

[41]P. Varghese, R. R. Silbar, and M. M. Sternheim, Phys. Rev. C 14, 1893 (1976).

[42]A. S. Carroll *et al.*, Phys. Rev. C 14, 635 (1976).

[43]S. E. Vigdor *et al.*, Bull. Am. Phys. Soc. 21, 984 (1976).