The (π^+,p) and (π^+,d) Reactions on Light Nuclei

MASTER

L

K. G. R. Doss, P. D. Barnes, N. Co[redacted]ella, S. A. Dytman,

R. A. Eisenstein, C. Ellegaard, F. Takeutchi, W. R. Wharton

Carnegie-Mellon University

Pittsburgh, Pennsylvania 15213

and

J. F. Amann

Los Alamos Scientific Laboratory

Los Alamos, New Mexico 87545

Abstract

The (π^+,p) and (π^+,d) reactions on 1P shell nuclei are studied between T_π = 32 and 81 MeV. Both the cross-sections to the continuum and to discrete two body final states are given.

The spectra and angular distributions of the (π^+,p) continuum are interpreted in terms of a two-nucleon pion absorption mechanism. The $^{13}C(\pi^+,p)$ spectra of discrete states is similar to the $^{13}C(p,d)$ spectra at the same momentum transfer. The two-neutron pickup (π^+,d) reaction is found to strongly favor transitions in the 1p shell of angular momentum transfer, L = 2. The relative strength of these transitions varies the same way as the corresponding (p,t) cross sections. No L = 0 transitions are clearly identifiable. There is an indication of the S = 1 $^7Li(\pi^+,d)$ ^5Li(16.7 MeV) $3/2^+$ transition contrary to the prediction that S = 1 transitions are suppressed. The (π^+,d) angular distributions are compared to the calculations of Betz and Kerman.

II. Experimental details

A. Experimental overview

This experiment was done at the Clinton P. Anderson Meson Physics Facility (LAMPF) using the Low Energy Pion (LEP) beam line [Bur 759]. We use a stack of 8 intrinsic germanium crystals (8GE) to detect the particles scattered from the target. Three multi-wire proportional chambers are used to calculate the trajectory of the particle from the target to the detector. Veto scintillators surround the germanium detectors to reject the particles that did not stop in the crystals. Two air-pressure ionization chambers downstream of the target monitored the intensity of the incident pion beam. A 3-scintillator telescope looked at the particles scattered from the target and provided an additional beam monitor.

The ^{7}Li and ^{12,13}C and $(CH_2)_n$ targets were 0.15 to 0.5 gm/cm^2 thick. The 0.48 gm/cm^2 ^{13}C target was made from ^{13}C powder with kraton binder by the WX-Z division of LASL. The ^{10}B target was a powder enclosed between mylar sheets. D_2O and H_2O (either ^{16}O and 98% enriched ^{18}O) water targets were made by glueing stretched 1 mil mylar to each side of a stainless steel frame, and filling with a syringe through a hole. A similar procedure but with stretched aluminum sheets was used to make hydrazine (N_2H_4) targets.

The uniformity of thickness of the liquid targets was determined by measuring the relative attenuation of beta rays from a strontium source through the different parts of the target. The initial nonuniformity in the thickness was about 10% for the 0.24 to 0.55 gm/cm^2 targets. It worsened by a factor of 2 or more after several days due to stretching of the mylar. The hydrazine targets were stable for only a few days since the liquid reacts with the epoxy binding the aluminum sheets to the stainless steel frame.

B. Germanium Detectors

The germanium detector stack used in this experiment was developed by the detector group at Lawrence Berkeley Laboratory [ ]. The detector consists of a stack of eight cylindrical intrinsic germanium crystals of thicknesses ranging from 0.25 to 1.2 cm. The diameter of the crystals is approximately 4 cm. The crystals are held in place in a copper holder which is in contact with a reservoir of liquid nitrogen in a dewar. Annular rings made of boron nitride (a good thermal conductor and an electrical insulator) provide the crystals thermal contact with the copper holder. These are called 'cold fingers' and have a 3.5 cm diameter hole to let the particles pass through.

The total effective thickness of this stack is about 8 cm of germanium. With this we can detect pions of maximum energy of 100 MeV, protons of 200 MeV and deuterons of 300 MeV. The minimum energy to identify these particles is determined by the thickness of the first crystal in the stack, which is 0.25 cm. This implies a minimum energy for pions of 15 MeV, 30 MeV for protons, 50 MeV for deuterons.

In measuring the energy of charged particles using this detector, inaccuracies can arise in the following ways: (i) If the particle, through coulomb multiple scattering escapes from the stack without depositing all its energy. (ii) If it loses a significant portion of its energy in the deadlayers. (iii) If it passes through the 'cold fingers' in going between crystals. (iv) If it has a nuclear interaction in a crystal and (v) finally, for unstable particles like pions or muons, if it decays and a varying amount of energy is deposited in the crystals by its decay products. We estimate the contribution of multiple scattering to the efficiency using a monte carlo code ANGLE [Doss 75]. The program ANGLE simultes the passage of particles through a stack of detectors taking into account the coulomb multiple scattering of particles and energy loss straggling. It includes the effects due to deadlayers and cold fingers and ignores the effects due to nuclear interactions and particle decay. We obtain the efficiency correction from nuclear interactions from previous measurements of nuclear reaction cross-sections for the various particle [Eisberg 72,77]. For pions, we assume that the nuclear reaction cross-section is about the same as that for protons. We estimate the loss of pions due to π-μ-e decay to be 15% based on analysis of in-beam runs. From these factors, we can calculate the total efficiency for detecting the particles as a function of its energy. The result of multiple scattering calculations show that the efficiency to detect particles decreases as the particle has higher energy and stops in later detectors. Due to the effects of the cold fingers, the efficiency has a staircase shape as a function of incident energy, remaining approximately a constant for particles stopping in the same crystal. The highest energy pions, protons, and deuterons detected in this experiment have efficiencies of about 40%, 50%, and 60% respectively.

There are a few methods by which we can experimentally check our efficiency calculation. The energy of elastically scatterd pions from protons (in a polyethylene target) varies with scattering angle; using ~~the~~ this and the known differential cross-section of π^+p scattering [Bertin 76], we can determine the relative variation of pion detection efficiency with pion energy. To cover the full pion energy range of interest it is necessary to choose several incident pion energies. Figure 1 shows that this measured efficiency is consistent with the staircase shape of the efficiency from the monte carlo calculation.

Another method used to check our efficiency calculations was to detect the protons from the $\pi^+d\to pp$ reaction at a forward angle and at the complementary back angle. The cross-sections for these two angles are kinematically related and the efficiency variation with proton energy can be checked without using the knowledge of the magnitude of the $\pi^+d\to pp$ cross section. This was done at complementary angles of 37 and 106 degrees for an incident pion energy of 105 MeV. This determines the ratio of the proton efficiencies for 84 and 150 MeV to be $\varepsilon(150)/\varepsilon(84) = 0.73$ which is consistent with the calculated ratio of 0.68 to within 10%.

Using these efficiency calculations the absolute cross section is obtained either by measuring and normalizing to the π^+p elastic scattering cross section obtained from the Dodder phase shifts [ ] or to the known $\pi^+d\to pp$ cross sections [ ]. When both normalizations were used they were found always to agree to within the experimental error of about 15%.

The GE crystals are oriented such that the Li contact deadlayers (50-100 μm) on crystals 2 and 3, 4 and 5, and six and seven face each other. The energy loss in a deadlayer cannot be corrected for if the particle stops in the deadlayer. However, for those particles which pass through the deadlayer and deposit energy in the next crystal a correction can be made. This is shown in figure 2 ([illegible]). Figure 2a shows the measured energy spectrum of the GE detector placed in a low intensity beam. The proton energy is adjusted so that most protons stop near the 2,3 deadlayer. Figure 2b shows the same data restricted to events depositing energy in crystal 3. We can see that the measured energy of these protons is up to 5 MeV less than events stopping in crystal 2 even though the beam is nearly monochromatic. If E is the energy of the particle before it enters the deadlayer, and E' the energy measured in the last crystal, then the particle identification P is given by

$$P = (E^{\alpha} - E'^{\alpha})/D \tag{1}$$

where D is the thickness of the deadlayer. Solving for E,

$$E = (E'^{\alpha} + P D)^{1/\alpha} \tag{2}$$

Now, the utility of the in-beam spectrum becomes obvious. We can adjust the value of D so that the corrected energy of proton for the particles going through the deadlayer is the same as the energy of proton that did not enter the deadlayer, thus determining the deadlayer thickness. Fig. 2-c shows the corrected spectrum with D = ?. This determination of D has uncertainties due to straggling in energy loss and an accuracy of 20% is expected. Since the deadlayer corrections to energy are usually less than 1 MeV the error in the corrected energy is quite small. Once D is determined, equation 2 gives the corrected energy for any particle.

The particle identification PID for a particle reaching the nth crystal, can be calculated n-1 ways by choosing D in eqn. 1 as the thickness of either the first 1,2,...n-1 crystals and defining E' as the energy deposited in the last n-1,n-2,...1 crystals respectively. Requiring all PID's to agree results in a clean PID spectrum. For example the PID for particles stopping in crystal 4 is shown in fig. 3.

The energy calibration of the GE crystals was obtained by using γ-sources and high gains on the amplifiers. The decrease in the gain necessary for the experiment was measured by observing the change in height of a pulser signal. Comparing runs separated by one year, we found one of the runs had a systematic calibration error of 2-4% for all crystals. Fortunately the peaks in the proton spectra are readily identificable with the known levels of the residual nucleus and the lack of an accurate calibration was not a major problem. For deuteron spectra, however, due to the low cross-section and poor statistics, we need to know the peak positions more accurately. So an empirical procedure based on the known observed peaks in the proton and pion spectra was used to predict the locations of the expected peak positions in the deuteron spectra. This also effectively corrected for straggling loses in the target, air, etc. The error in the predicted location of the (π^+,d) transitions is estimated to be about 0.5 MeV.

III. The (π^+,p) and (π^+,d) continuum data

We have measured the inclusive proton cross-sections for positive pions of energy 34, 47, 65 and 81 MeV incident on ^{12}C. Some typical spectra for 34 MeV are shown in Figure 4. (The dip seen at about 50 MeV in the proton spectra is due to the energy loss in the deadlayer between 8GE2 and 8GE3.) These spectra are in general characterized by a broad bump at approximately the energy corresponding to the kinematics of the $\pi^+d\rightarrow pp$ reaction. The position of the bump moves with scattering angle at approximately a rate expected in the $\pi^+d\rightarrow pp$ reaction, suggesting that the protons observed in the bump are from absorption of a pion on two nucleons.

The peak value of the observed cross-section is plotted in Figure 5 as a function of scattering angle. The curve drawn is proportional to the lab angular distribution of the $\pi^+ d \rightarrow pp$ reaction. We see that the peak value cross-section has a shallow minimum at a scattering angle of about 90 degrees, shallower than the minimum seen in the $\pi^+ d \rightarrow pp$ process at the same energy. The scattering of the pion before it is absorbed, the fermi motion of the nucleon pair on which it is being absorbed and the final state interactions of the exiting protons all tend to fill the minimum observed in the $\pi^+ d \rightarrow pp$ reaction. The energy-integrated cross-section shown on the same figure has a similar angular distribution. The low limit of integration was equal to $E_{low}=E_k-E_{offset}$, where E_k is the energy of the proton from $\pi^+ d \rightarrow pp$ reaction at the angle of interest, and E_{offset} is a constant. The shape of the integrated cross-section was found to be independent of the value of E_{offset}, for small changes in E_{offset}. Not only does the double differential cross section $d\sigma/d\Omega dE$ at $E = E_k$ have the same angular distribution as the energy-integrated differentail cross-section, they also have the same energy dependence, both increasing by 25% as the pion energy increases from 34 to 81 MeV. The elementary $\pi^+ + d \rightarrow p + p$ increases by a factor of 2 over the same energy region.

The similarity of the angle and energy dependence of the peak cross-section suggests a common reaction mechanism for the production of all high energy protons. The fact that the energy location of the peak follows the $\pi^+ d \rightarrow p + p$ kinematics suggests that the pion is annihilating on two nucleons. In this 2 nucleon absorption process the two nucleons are expected to recoil at nearly 180° with respect to each other. If the reaction takes place on the nuclear surface, one of the nucleons would always escape without passing through the nucleus. In this situation, we would expect to see a very dominant peak in the spectrum at E_k, the energy of the proton using the $\pi^+ d \to pp$ kinematics. Instead we see only a slight enhancement of the cross section at E_k. For the two-nucleon absorption model to be consistent with the data, the absorption must take place predominantly deep inside the nucleus, allowing both nucleons to scatter on their way out of the nucleus.

Recently McKeown et al. [ ], using data between T_π = 100 and 220 MeV, have shown that the effective number of nucleons, N, sharing the momentum and energy of the annihilated pion is 3 for A = 12, and increases to 5.5 for A = 181. Doss and Wharton [ ] have examined the A dependence (near the 3-3 resonance) of (1) the total pion absorption cross section (2) the effects number of nucleons sharing the pion momentum and energy and (3) the proton yields from π^+ and π^- induced reactions. They show that the A-dependence can be explained by basic geometrical arguments assuming the pion penetrates the nuclear volume and annihilates on a pair of nucleons.

We also have simultaneously measured the continuum deuteron spectra for E_d > 70 MeV. There is no structure and the cross section falls off monotonically for higher deuteron energy. The energy integrated cross-section for E_d > 70 MeV is shown in Figure 6 along with the energy integrated angular distributions for protons, for E_p > 50 MeV. The cross-section is forward peaked and has approximately the shape of the proton cross-section, suggestive of a pickup mechanism for the deuteron production.

IV. (π^+,p) transitions to discrete states

Figure 7 shows the spectra of the $^{13}C(\pi^+,p)^{12}C$ reaction at T_π = 32 MeV and θ = 55 and 95°. The resolution is about 2 MeV and is dominated by target thickness effects. With this resolution it is impossible to resolve the 14.1, 15.1, and 16.1 MeV states and certain assumptions were made in fitting the spectra. The spectra have been fit using the peak shape of the 4.4 MeV 2^+ transition. The positions of the peaks were fixed relative to the 4.4 MeV peak location. A smooth background which begins near the beginning of the three body continuum and varies smoothly from angle to angle was drawn by eye. In the initial fitting of the 55° (95°) spectrum ~~and~~ the 16.1 and 15.1 (15.1 and 14.1) MeV transitions were assumed to have equal strength. After adjusting their strength, which is subtracted with the background from the spectrum, the left-over counts are fit using additional peaks at the appropriate excitation energy. In this second step, additional counts were assigned to the 15.1 MeV state in the 95° spectrum. Although this procedure gave us cross sections for the 13.5, 14.1, 15.1, and 16.1 MeV states, only the cross-sections to the 15.1 and 16.1 MeV states were stable against variations in the initial fitting conditions. The cross sections are listed in table I along with errors which were estimated by making reasonable changes in the background and fitting procedure.

In fig. 8 the single nucleon pickup spectroscopic strengths for these states are given. Interestingly, the 4.4 MeV 2^+ state is much stronger than the 16.1 MeV 2^+ (T = 1) state although their spectroscopic strengths are nearly equal. Also the 15.1 MeV L^+ (T = 1) state is much stronger than the 12.7 MeV 1^+ state although their spectroscopic strengths are nearly equal. Figure 8 shows that this same behavior occurs for the (p,d) reaction [Smith 78] near the same momentum transfer. These relative intensities of the 2^+ and 1^+ states suggests the importance of two-step processes involving inelastic scattering of either the initial pion (proton) or the final proton (deuteron). Such inelastic processes would favor the collective 4.4 MeV 2^+ state over the 16.1 MeV 2^+ state and also favor the 15.1 MeV 1^+ state over the 12.7 MeV 1^+ state. The 15.1 is favored because the nucleon magnetic moments strongly favor T = 1 M1 transitions over T = 0 M1 transitions. These two-step processes become more important [ ] at large momentum transfer because the inelastic process absorbs some of the momentum transfer.

Further evidence for the two-step process is the shape of the angular distribution. Using the DWBA coupled channels code, chopper, [ ] we find that the differential cross section at large angles relative to the forward angles is generally larger for two-step processes than for one-step pickup processes. Experimentally the angular distributions of the 4.4 and 15.1 MeV states fall off much less steeply than the angular distributions of the ground state and 16.1 MeV state.

Other cross sections which we measured were at T_π 47 MeV $^{12}C(\pi^+,p)$ [ ] and at T_π = 65 MeV, $^{12}C(\pi^+,p)^{11}C$(g.s.) 30° - 48±6 μb/sr and 120° - 48±0.5 μb/sr, and $^{16}O(\pi^+,p)$ ^{15}O(g.s.) 30° - 2.3 ± 0.9 μb/sr in the laboratory frame. Recently Wharton and Keister [ ] using this data and other data have shown that a single neutron pickup distorted-wave calculation has serious problems in describing the systematic energy and A-dependence of the cross sections of ground state transitions in the 1p shell. They briefly examined the data in terms of a two-nucleon absorption model and found that features of the two-nucleon model showed a good possibility of describing the systematics of the data.

V. (π^+,d) transitions to discrete states

Simultaneously with the (π^+,p) data collection, the (π^+,d) data was also collected. The particle identification, figure 3, was good enough to obtain essentially pure spectra. These spectra are shown in figures 9-14. The (π^+,d) reaction, similar to the (p,t) reaction is a two-neutron pickup reaction. In contrast to the (p,t) reaction where $0^+\to0^+$ ground state transitions often dominate the spectra, no such transitions are clearly identifiable in the (π^+,d) spectra. There is a complete lack of counts in the region of the 0^+ ground state for all $^{18}O(\pi^+,d)^{16}O$ and $^{16}O(\pi^+,d)^{14}O$ spectra. There is some hint of the $^{12}C(\pi^+,d)^{10}C$ 0^+ ground state transition, but it is much weaker and not clearly resolved from the transition to the $^{10}C(3.36)$ 2^+ state. Not only do we have poor statistics and energy resolution (2.0-3.0 MeV) but our absolute energy calibration is uncertain to 0.5 MeV, making our spectra analysis a little difficult.

These $0^+\to0^+$ transitions are necessarily zero angular momentum transfer, L = 0, processes. If the dominant pion partial waves are $\ell_\pi = 0,1,2$, angular momentum conservation restricts the deuteron impact parameter to less than 0.5 fermi. In contrast, a L = 2 transition would allow deuteron impact parameters larger than 1.0 fermi. The only L = 0 transition which is clearly identifiable in our spectra is the $^7Li(\pi^+,d)$ $^5Li(gs)$ $3/2^-\to3/2^-$ transition. At T_π = 65 MeV $\theta = 30°$ the laboratory cross section for this transition is about 0.22 ± .06 μb/sr. Although this transition is precominantly L = 0 it also has a L = 2 amplitude [d1].

Removing two neutrons from the p shell restrict the angular momentum transfer to 0 and 2. Our spectra clearly show that the L = 2 transitions are generally much stronger than the L = 0 transitions. Data at forward angles on four of these transitions $^{10}B(\pi^+,d)$ $^{8}B(gs)2^+$, $^{12}C(\pi^+,d)$ $^{10}C(3.36)2^+$, $^{13}C(\pi^+,d)$ $^{11}C(gs)3/2^-$, and $^{18}O(\pi^+,d)$ $^{16}O(9.85)2^+$ are given in table II. The (p,t) reaction at $T_p \sim 45$ MeV shows a nearly pure L = 2 angular distribution for all four of these transitions, with a maximum in the angular distribution occuring near 25°. The (p,t) cross section at this maximum is given in column 5 of table II. As expected, both the (π^+,d) and (p,t) reactions are proportional to the two-neutron spectroscopic strength. Although the cross sections for these transitions vary by more than a factor of 10, the ratio $d\sigma(\pi^+,d)/d\sigma(p,t)$ is identical within experimental error for the first three transitions. The probable reason why the $^{16}O(9.85)$ transition is not seen in (π^+,d) is because the larger momentum transfer, 651 MeV/c, should inhibit this transition.

Having examined the favoring of large angular momentum transfer for the (π^+,d) reaction, we turn to the spin dependence of the reaction. The (p,t) reaction can pick up two neutrons only in a S = 0 state. S = 1 transitions are, in addition, allowed for the (π^+,d) reaction. To examine the spin dependence, we look at the $^{7}Li(\pi^+,d)^{5}Li$ reaction. The only narrow state which is known to exist in the particle unstable ^{5}Li nucleus is the $3/2^+$ state at 16.7 MeV. This state is known to be a two-particle-1 hole state with configuration $^{4}S_{3/2}$ (the superscript is 2S+1) [d6]. Since the ^{7}Li ground state is $2p_{3/2}$, the transition between the two states must be S = 1, L = 1. In the (p,t) reaction it is forbidden and not seen [d1]. Interestingly there is a narrow peak in the $^{7}Li(\pi^+,d)$ ^{5}Li spectrum in figure 9, centered at $E_x = 17$ MeV with 7 counts. The only other states besides the 16.7 MeV $3/2^+$ state known to exist in this vicinity are very broad states at E_x = 18 and 20 MeV. We extract a laboratory cross section for this peak of 0.38 μb/sr at T_π = 65 MeV, θ_{Lab} = 30°.

Next, we wish to examine the $^{13}C(\pi^+,d)$ ^{11}C spectra in figure 12. In addition to the ^{11}C(gs) peak there is a strong peak in the vicinity of the 6.48 MeV $7/2^-$ and 4.3 MeV $5/2^-$ states, which becomes dominant in the spectra at back angles. These states are well described as $^{12}C(4.4)2^+ \otimes 1P^{-1}_{3/2}$ configurations and are strongly seen in other large momentum transfer pickup reactions (π^+,p) and (p,d) [d7]. These states have small spectroscopic strength with the target and presumably are populated through two step processes involving inelastic quadrupole excitation. Such two step processes are conducive to large momentum transfer reactions because the inelastic process can absorb some of the momentum transfer. The (π^+,d) angular distribution to these $7/2^-$ and $5/2^-$ states are less forward peaked than the ground state transition (see figure 15). This is similar to the (π^+,p) angular distributions to these states and is characteristic of a two-step process (see section III).

The only (π^+,d) calculations [d8,d9] which have been performed are based on a single-step interaction which couples the initial state $(\pi^+\ ^{12}C)$ to the final state $(d + {}^{10}C)$. A single nucleon absorbs the pion and picks up a second nucleon immediately thereafter. The nucleon-nucleon interaction necessary to accomplish this last step is contained in the deuteron wave function. In this model the S = 1 transitions are a factor of 100 weaker than the S = 0 transitions. Therefore it would be surprising if the structure near E_x = 17 MeV in the $^{7}Li(\pi^+,d)$ ^{5}Li reaction is the L = 1, S = 1 16.7 MeV transition.

Using this model,
Betz and Kerman [d9] have included distortion in both the pion and deuteron wavefunctions. The off-shell propagation of the pion increases the calculated cross section at large momentum transfer (large angles) relative to the Born approximation. The strong damping of the deuteron wave in the nuclear medium suppresses the forward angle cross section by almost three orders of magnitude. The net effect is that the (π^+,d) differential cross section is largest at 180°. We checked this by measuring the $^{12}C(\pi^+,d)\ ^{10}C$ cross section at 30° and 120°. The differential cross section to the 0^+ g.s. plus 2^+ 3.35 MeV states at T_π = 65 MeV are shown in figure 16 along with the Betz and Kerman calculations at 50 MeV. Although we can not clearly resolve the 0^+ and 2^+ states it appears as if the 2^+ transition is at least a factor 4 larger than the 0^+ transition. The calculation shows the 2^+ to be only 20-40% larger at 30° and 120°. The 120° to 30° cross section ratio is calculated to be about 3.2 ± 1.1 larger than to experiment, but nevertheless both the magnitude and shape of the 2^+ angular distribution are remarkably well reproduced. The main failure of the model appearing here is the underestimate of the L-dependence on the cross section. It is a puzzle why the model doesn't give a stronger L-dependence. The strong attenuation of the deuteron wave function, which more heavily weights the surface region of the nucleus, will naturally lead to a severe angular momentum mismatch for small angular momentum transfers.

All (π^+,p) data to states with large spectroscopic strength in the 1p shell [ ] obey a simple exponential behavior with momentum transfer, q, at forward angles, $\sigma(\theta) = C\, e^{-q/\lambda}$. Interestingly Betz and Kerman predict a similar exponential behavior for the (π^+,d) reaction but with a slope, $1/\lambda = (22\ \text{MeV/c})^{-1}$, which is twice as steep as observed in $^{12}C(\pi^+,p)$, $(41\ \text{MeV/c})^{-1}$. Experimentally, the data gives even a steeper stope but within the large error bars is consistent with the calculation (see figure 17).

Another prediction of the Betz-Kerman calculation is that the $^{18}O(\pi^+,d)$ ^{16}O(g.s.) transition should be a factor of 10 larger than either the $^{12}C(\pi^+,d)$ ^{10}C(gs) or the ^{10}C(3.36 MeV) transition. In contrast the observation shows it to be at least a factor of 2 weaker than the ^{10}C(3.36 MeV) transition. This faulty prediction comes from two effects: 1) the ^{18}O ground state is a well known pairing condensate with a constructive, coherent mixture of $(1d_{5/2})^2$, $(1d_{3/2})^2$ and $(2S_{1/2})^2$ confugurations, 2) the $(2S_{1/2})^2$ and $(1d_{3/2})^2$ (π^+,d) transition matrix elements are very large. Whether effects 1 and 2 are valid as applied to the (π^+,d) reaction is primarily a question of reaction mechanism and only secondly a question of nuclear structure. Ultimately there may be some interesting nuclear structure questions because two-neutron pickup reactions have never been studied at such high momentum transfer with any reaction. Betz and Kerman also make a prediction that the (π^+,d) forward angle cross-section increases a factor of 10 from $T_\pi = 50$ to 87.5 MeV. The data for $^{12}C(\pi^+,d)$ $^{10}C(3.36)$, $\theta = 30°$, shows no increase in cross-section between $T_\pi = 49$ and 65 MeV. The model for the (π^+,d) reaction has shown both success and failure in describing the data. Whether the successes, such as predicting the approximate magnitude of the cross-section is fortuitous or indicative of the model's basic validity must await further study.

Table I

$^{13}C(\pi^+,p)$ Lab Cross Sections (μb/sr) at 32 MeV

E_{ex}/θ	35	55	75	95	115
0.0	8.9 ± 1.9	2.6 ± 0.6	0.96 ± 0.6	0.17 ± 0.11	0.36 ± 0.24
4.4	76.4 ± 5.9	33.0 ± 2.3	20.8 ± 2.8	10.7 ± 1.1	11.4 ± 1.3
7.6	4.2 ± 1.7	2.5 ± 0.8	< 0.8	0.54 ± 0.28	0.22 ± 0.22
9.6	8.9 ± 2.2	4.3 ± 1.1	5.0 ± 1.6	0.86 ± 0.35	1.32 ± 0.6
12.7	< 17	< 3.1	< 3.1	< 1.2	< 1.4
15.1	< 20	17.0 ± 5.8	10.4 ± 3.5	8.6 ± 2.2	13.7 ± 3.8
16.1, 16.6	36.0 ± 12	17.0 ± 6	4.2 ± 4.2	< 1.6	< 2.9

Table II

L = 2 (π^+,d) cross sections

Final state	T_π	θ_d	q (MeV/c)	$\frac{d\sigma}{d\Omega}(\pi^+,d)$ (μb/sr)	$\frac{d\sigma}{d\Omega}(p,t)_{max}$ (mb/sr)	$\frac{d\sigma(\pi^+,d)}{d\sigma(p,t)}$ (x 10^{-3})
$^{8}B(gs)2^+$	48	30	606	0.07 ± 0.07	0.09[1)]	1.3
$^{10}C(3.362^+$	48	30	606	0.51 ± 0.21	0.22[2)]	2.3
	65	30	625	0.30 ± 0.07		1.4
$^{11}C(gs)3/2^-$	32	35	626	1.6 ± 0.8	1.0[3)]	1.6
$^{16}O(9.85)2^+$	41	30	651	< 0.16	0.18[4)]	<0.9
				< 0.26		<1.4

1) reference d2

2) reference d3

3) reference d4

4) reference d5

Some References

d1. J. Cerny et al., Phys Rev. 152 (1966) 950.

d2. NP A141 (1970) 158.

d3. NP A97 (1967) 510.

d4. PR C11 (1975) 64.

d5. PRL 35 (1975) 357.

d6. NP A147 (1970) 293.

d7. J. F. Amann et al., PRL C12 (1978) 758.

d8. R. A. Eisenstein and G. A. Miller, Phys. Rev. C11 (1975) 2001.

d9. M. Betz and A. K. Kerman, submitted to Nuclear Physics.