Cross sections for (π^+, p) reactions on ^{6}Li, ^{9}Be, ^{12}C, and ^{16}O†

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Measurements of the (π^+, p) reaction on ^{6}Li, ^{9}Be, ^{12}C, and ^{16}O have been made for 70-MeV pions. A magnetic spectrometer was used to momentum analyze the pion beam while thick NaI(Tl) detectors were used to determine the proton energy. The experimental resolution was 3 MeV. Data from the ^{9}Be and ^{16}O targets were taken around a laboratory scattering angle of 25°. The number of (π^+, p) events from these nuclei was not significantly greater than background contributions, and therefore upper limits on the cross section are presented. Data from the $^{12}C(\pi^+, p)^{11}C$ reaction were obtained at proton emission angles of 20 and 32° (lab), while for ^{6}Li, measurements were made over the angular range from 33 to 90°. Our experimental cross section for the $^{12}C(\pi^+, p)^{11}C$ reaction, obtained by integrating over ^{11}C excitation energies from 0 to 8 MeV, did not agree well with existing theoretical predictions. Results from the $^6Li(\pi^+, p)^5Li$ reaction indicated excitation of the $p_{1/2}$ state of ^{5}Li. The cross section for this reaction decreased rapidly for emission angles less than 60°, while at larger angles the cross section was constant within the measured range.

[NUCLEAR REACTIONS ^{6}Li, ^{9}Be, ^{12}C, $^{16}O(\pi^+, p)$, $E = 70$ MeV, measured $\sigma(\theta)$.]

I. INTRODUCTION

The study of the (π^+, p) reaction is attractive for a variety of experimental and theoretical reasons. Experimental measurements are comparatively simple since the capture leading to low-lying states of the residual nucleus results in two-body final states with distinct signatures.

The high momentum transfers (>500 MeV/c) involved provide a method for probing the hard-core components of the nucleon-nucleon force. This reaction has been suggested[1,2] as a means to test the perturbation theory approach used in the study of pion-absorption phenomena. In addition, the study of this process may yield information concerning details of the pion-absorption mechanism, such as the effects of initial-state correlations and pion-rescattering terms.

Theoretical calculations have been performed for the (π^+, p) reaction[1-5] and the related (p, π^+)[4-9] process on a variety of nuclei. Calculated cross sections for the $^{12}C(\pi^+, p)^{11}C$ reaction at a laboratory angle of 25° ranged from 60 μb/sr when plane waves were used to describe the pion and proton,[1] to 13 mb/sr when distorted waves were used.[2] A previous experimental measurement made at a laboratory angle of 0° and with 14-MeV resolution yielded a cross section of 430 ± 110 μb/sr for capture leading to the ground and low-lying excited states of ^{11}C.[10]

A measurement[11] of the related process $^{12}C(p, \pi^+)^{13}C$, at a proton energy of 185 MeV and an angle of 25°, in which discrete final states of ^{13}C were resolved, produced a cross section of approximately 0.250 μb/sr for the ground state of ^{13}C. The cross section summed over states below 8 MeV excitation was about 2 μb/sr. A detailed balance calculation using these data yields a cross section of 6 μb/sr for the $^{13}C(\pi^+, p)^{12}C$(g.s.) reaction, which is about two orders of magnitude lower than the value of Ref. 10 measured for the $^{12}C(\pi^+, p)$ reaction but summed over a number of low-lying states.

The theoretical interest in these reactions and the limitations of previous (π^+, p) experimental results led us to use our (π^+, pp) apparatus for a measurement of the process on a variety of light nuclei. In this paper we present results obtained from the nuclei ^{6}Li, ^{9}Be, ^{12}C, and ^{16}O.

II. THEORETICAL BACKGROUND

The simplest description of the absorption of a pion leading to the emission of a single nucleon is given by assuming absorption on a single uncorrelated nucleon within the nucleus. From first-order time-dependent perturbation theory, the expression for the cross section is

$$\sigma(\theta, \phi) = \frac{M}{(2\pi)^2} E_\pi \frac{k}{q} \sum_f |\langle f|H|i\rangle|^2 , \qquad (1)$$

where M and μ are the nucleon and pion masses; q, k are the momenta of the pion and outgoing nucleon, and $E_\pi = (\mu^2 + q^2)^{1/2}$. The Hamiltonian H is usually taken to be the Gallilean invariant form of the nonrelativistic pseudoscalar-pseudovector interaction (see, e.g., Ref. 1)

$$H \propto \frac{f}{\mu} \sum_{i=1}^{A} \left[\vec{\sigma} \cdot \vec{\nabla}_\pi \vec{\tau} \cdot \vec{\phi} - \frac{\mu}{M} \vec{\tau} \cdot \vec{\phi} \vec{\sigma} \cdot \vec{\nabla}_N \right]_i . \qquad (2)$$

Here f is the pion-nucleon coupling constant, $\vec{\phi}$ is the pion field, μ and M are the masses of the pion and nucleon, $\vec{\sigma}$ and $\vec{\tau}$ are the Pauli spin and isospin matrices.

Calculations employing this formulation have in the simplest case used plane waves to describe the pion and outgoing proton. These calculations use harmonic-oscillator wave functions to describe the state of the absorbing neutron in the initial nucleus.[1] Optical-model wave functions have also been used to represent the pion and proton together with neutron wave functions generated by a Woods-Saxon potential.[2] Hartree-Fock methods have been employed to describe the initial nucleus in a calculation using plane waves for the pion and proton.[3] The use of the Hartree-Fock representation serves to introduce correlations between nucleons in the initial state.

Theoretical calculations, based on the dominance of a two-nucleon mechanism, have been performed for the (p, π^+) reaction.[6-8] In the case of the (π^+, p) process, the pion would be captured on two nucleons with one being ejected and the other absorbed. The simplest treatment relates the cross section for pion production to the cross section for the two-nucleon process $p + p \to d + \pi^+$.[6] With this approach Ingram, Tanner, and Domingo[6] have calculated the ^{11}C$(p, \pi^+)^{12}$C(g.s.) cross section for incident protons of energy 215 MeV. The corresponding ^{12}C$(\pi^+, p)^{11}$C(g.s.) cross section obtained by detailed balance will be compared with our data in Sec. IV.

Other calculations which employ the two-nucleon mechanism exist for π^+ production at high energies. Reitan has calculated the ^{12}C$(p, \pi^+)^{13}$C cross section for 600-MeV protons assuming a model in which the pion is emitted by one of the bound nucleons and is rescattered through the (3, 3) resonance by the incident proton.[7] More recent calculations, based on the Mandelstam model of pion production by two nucleons, have been made by Reitan for the ^{4}He$(p, \pi^+)^5$He and the ^{12}C$(p, \pi^+)^{13}$C reactions at proton energies of 600 and 185 MeV, respectively.[8]

The observation of the (π^-, p) or (p, π^-) process has been suggested as a test of the importance of the two-nucleon mechanism since these reactions cannot occur through the direct one-nucleon process. Recent experimental measurements of the ^{9}Be$(p, \pi^\pm)$ processes at 0° for 600-MeV protons have obtained a π^+/π^- ratio of between 100 to 200,[12] while measurements of the same reactions at 185 MeV, in which discrete final states were resolved, obtained for ground-state transitions a π^+/π^- ratio which varied from 30 to approximately 2 over the laboratory angular range from 35 to 125°.[13]

III. EXPERIMENTAL DETAILS

The experiment was performed at the Lawrence Berkeley Laboratory 184-in. cyclotron in conjunction with a measurement of the (π^+, pp) process on several light nuclei. The experimental setup is shown in Fig. 1. Positive pions of 70 MeV were produced when the external proton beam struck a copper production target. The momentum of each pion was determined by measurements of its position and direction at the entrance and exit of the bending magnet through the use of the hodoscope C_1 and the spark chamber planes S_1-S_7. The beam flux was 3×10^4 particles/sec, of which $62\pm5\%$ were π^+. The position and angle of the outgoing proton were measured with spark chamber planes mounted on the arms of a large scattering platform. The proton energy was determined through the use of 10-cm-thick NaI counters, and dE/dX was measured in two plastic scintillators mounted in front of the NaI crystals. Particle identification was achieved by the E-ΔE technique.

The protons from the ^{6}Li$(\pi^+, p)^5$Li process, with a maximum energy of 178 MeV, could be stopped in our NaI crystals. We were able, for this reac-

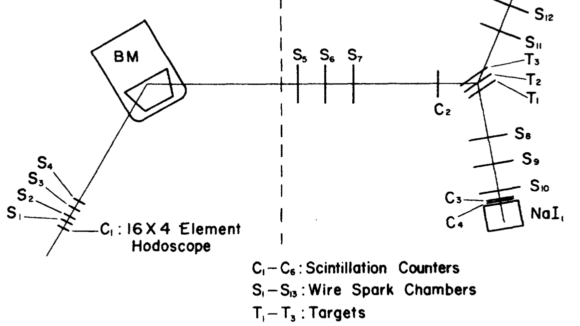

FIG. 1. Experimental geometry (overview).

tion, to cover a range of πp angles in the lab from 33 to 90°. For the measurement of the (π^+, p) reaction on ^{9}Be, ^{12}C, and ^{16}O, the NaI crystals were not thick enough to stop the emitted proton. For these nuclei data were taken at an angle of 25° with the experimental setup shown in Fig. 2. A copper absorber was added to decrease the proton energy, and two extra dE/dX detectors were used to improve the particle identification.

Data collection was controlled by an XDS Sigma 2 computer. All raw data were written on magnetic tapes for subsequent analysis. The kinematical and experimental parameters of interest for each event were calculated by an on-line analysis program and were displayed via histograms.

Three separate targets were used simultaneously to increase the event rate without substantially increasing the contribution to the over-all resolution due to target thickness. Events were assigned to one of the targets by reconstruction of the reaction vertex. Calibration for the NaI detectors was obtained from the overconstrained measurement of π^+ absorption on deuterium. The resolution in

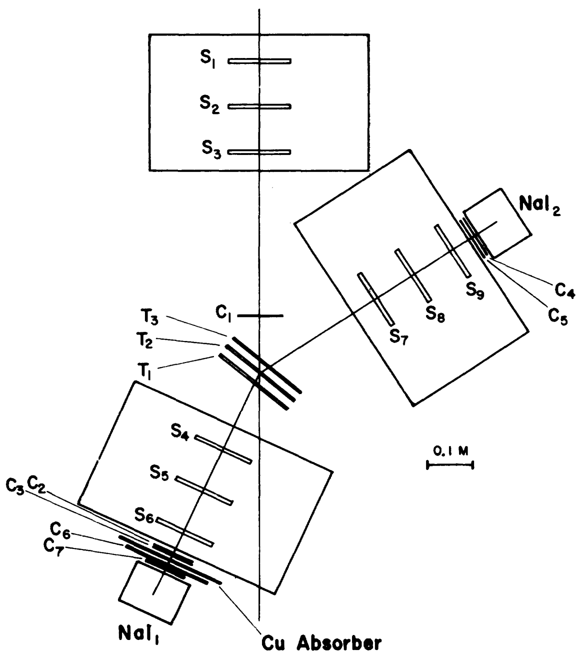

FIG. 2. Experimental geometry for (π^+, p) data on ^{9}Be, ^{12}C, and ^{16}O. S_1 through S_9 are wire spark chambers, T_1 through T_3 are target elements, and C_1 through C_5 are 0.15-cm plastic scintillation detectors. C_6 and C_7 are 0.32-cm-thick scintillation detectors which were added to improve the particle identification. The apparatus of the second arm located at a backward angle with respect to the pion beam was not actively used in the (π^+, p) measurements; instead it was used to provide a calibration for the NaI detectors through observation of the protons from the $\pi^+ + d \rightarrow p + p$ reaction.

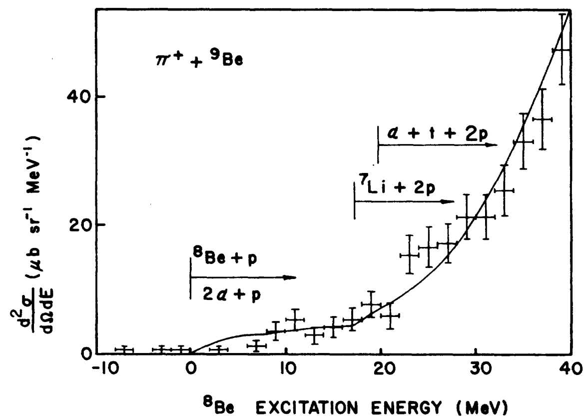

FIG. 3. Excitation energy spectrum for ^{8}Be. The curve represents the phase-space contribution from competing reactions in which a proton occurs in the final state. The curve has been adjusted to best fit the data.

excitation energy was 3 MeV full width at half maximum (FWHM); the precision was 1.5 to 2 MeV.

Corrections have been applied to the data to account for spark chamber and hodoscope inefficiencies, and for inefficiencies in the reaction vertex reconstruction. Corrections for the effects of nuclear interactions in the NaI crystal and the copper absorber (for data taken with the geometry of Fig. 2) were made using the calculations of Measday and Richard-Serre for proton loss in various materials,[14] and the experimental measurements of Palmieri and Wolfe.[15] The correction due to nuclear interactions was 24 to 28%.

Scattered pions can produce large pulses in the NaI detectors by undergoing charge-exchange reactions to π^0 with the subsequent generation of

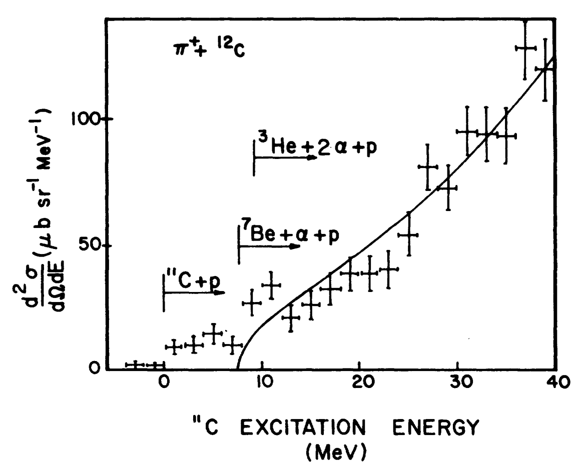

FIG. 4. Excitation energy spectrum for ^{11}C. The curve represents the contribution from competing reactions as described in Fig. 3.

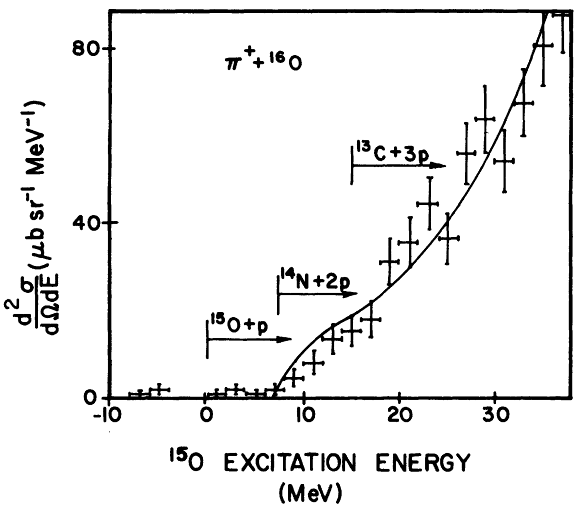

FIG. 5. Excitation energy spectrum for ^{15}O. The curve has been described in Figs. 3 and 4.

showers from the decay γ rays. Contamination electrons in the beam of momenta 160 MeV/c can also produce large pulses by virtue of shower production. Cuts made on the dE/dX spectrum eliminated most, but not all, of the background from scattered π's or electrons.

IV. RESULTS

A. ^9Be, ^{12}C, and ^{16}O

Measurements made with the experimental setup described in the previous section provided a determination of the momentum of both the incident pion, $\vec{q}$, and the outgoing proton, $\vec{k}$. Since the residual nucleus was not detected, a large background occurs from competing reactions involving multiparticle breakup. Therefore, only the cross section for (π^+, p) events leading to low-lying excited states of the residual nucleus below the continuum could be isolated.

The excitation energy spectra, which were analyzed by assuming that the residual nuclei were ^8Be, ^{11}C, and ^{15}O, are shown in Figs. 3–5. The thresholds for continuum background reactions in which a proton occurs in the final state are also shown. The curves represent contributions from these background reactions, as calculated from phase space, with relative amounts adjusted to best fit the data. Events occurring in these distributions have been integrated over a range of πp angles from 15 to 40°. The errors shown are statistical. The error in the absolute scale for the cross section is approximately 10%. Events occurring at negative excitation energies are presumably due to contamination from the scattered pions and electrons discussed previously. Such events establish a background level which provides a lower limit on our measured cross section.

We obtained events significantly greater than the contribution from background reactions only for ^{12}C. The events which occur in the region of excitation energy from 0 to 8 MeV correspond to possible contributions from the lowest seven states of the residual ^{11}C nucleus. Our resolution of 3 MeV did not permit separation of any of these

TABLE I. Cross sections (π^+, p) reaction.

Nucleus	$\Delta\theta$ Interval of integration (deg)	Integration interval in excitation energy (MeV)	Cross section (μb/sr)
^9Be	15–40	0–16	<46
^{12}C	15–25	0– 6	78 ± 30
^{12}C	15–25	0– 8	110 ± 39
^{12}C	26–38	0– 6	41 ± 18
^{12}C	26–38	0– 8	58 ± 23
^{16}O	15–40	0– 8	<17

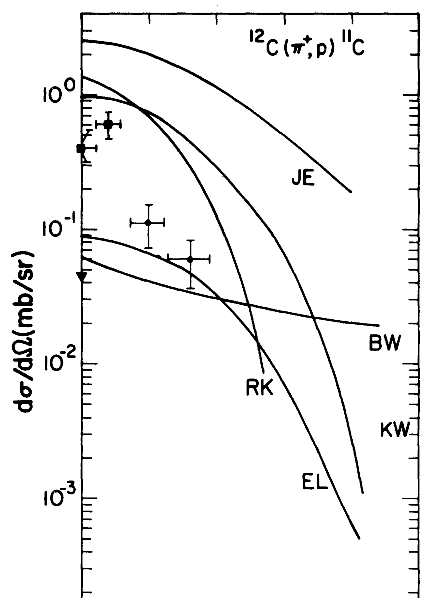

FIG. 6. Comparisons of the ^{12}C experimental results with existing theoretical calculations: ●: experimental results from this work; ■: experimental results from Witten, Blecher, and Gotow (Ref. 10); ▼: theoretical point at 0° for the reaction $^{12}C(\pi^+, p)^{11}C$(g.s.) as determined by detailed balance from the $^{11}C(p, \pi^+)^{12}C$(g.s.) cross section calculated in Ref. 6. The curves labeled EL, JE, KW, RK, and BW represent, respectively, the results of calculations by Eisenberg and Letourneux (Ref. 1), Jones and Eisenberg (Ref. 2), Kaushal and Waghmare (Ref. 3), Rost and Kunz (Ref. 4), and Wienke (Ref. 5).

levels.

For ^{12}C events we are able to present cross sections for two regions of outgoing proton angle: (a) the range from 15 to 25°, and (b) from 26 to 38°. The cross sections for these angular regions, integrated over various ranges of excitation energy, appear in Table I. The errors quoted in the table are due to statistical errors, uncertainties in the efficiencies used to correct the data, and the uncertainty in the energy precision.

Also presented in Table I are the results obtained from ^{9}Be and ^{16}O integrated over the indicated region in excitation energy. Because the results obtained for these two nuclei are not significantly greater than the scattered pion and electron contribution, the cross sections are considered to be upper limits.

In Fig. 6 we compare our results for the ^{12}C-(π^+, p)^{11}C reaction (summed over the first 8 MeV of ^{11}C excitation energy) with the previous experimental measurements of Witten, Blecher, and Gotow[10] and with existing theoretical calculations. The measurements of Ref. 10 were obtained for angles of 0 and 11°, and with an energy resolution of 14 MeV FWHM. They found cross sections of 430 ± 110 and 640 ± 130 μb/sr, respectively, for the two angles. Strict comparison of the data from the two experiments is difficult since the overlap in πp angles is small. However, our results are lower than the ones which they obtained.

The theoretical curves which appear in Fig. 6 have been calculated for capture on a $p_{3/2}$ neutron in ^{12}C. The curves labeled EL and JE are the result of calculations made by Eisenberg and Letourneux, and by Jones and Eisenberg for 50-MeV incident pions. In the first case (curve EL), plane waves were used to describe the pion and proton,[1] whereas in the calculation of JE, distortions of the pion and proton were included.[2] Calculated cross sections for 68-MeV pions are shown in curves KW and RK. In the calculation of Kaushal and Waghmare (curve KW) plane waves were taken for the pion and proton in conjunction with a Hartree-Fock model of the nucleus.[3] The curve labeled RK is based on a calculation of Rost and Kunz in which the (π^+, p) and (p, π^+) processes were treated as pickup and stripping reactions.[4] In the latter, a distorted-wave Born-approximation (DWBA) calculation was made in which the constant f appear- in Eq. (2) was treated as an adjustable parameter which was varied to fit measurements of the ^{12}C-(p, π^+)^{13}C reaction. The remaining curve (curve BW) results from a relativistic calculation of Wienke for 70-MeV pions in which field theory techniques were used.[5] In this approach Feynman graphs representing both the direct pion nucleon interaction of expression (1) and pion-rescattering terms were included. Plane waves were used for both the pion and proton, and the nuclei were described by harmonic-oscillator wave functions with exponential tails. A strong dependence of the cross section on harmonic-oscillator parameters is lessened somewhat by the inclusion of pion-rescattering terms which serve to redistribute the momentum transfer to two nucleons. Finally, the theoretical point, shown at 0°, was obtained

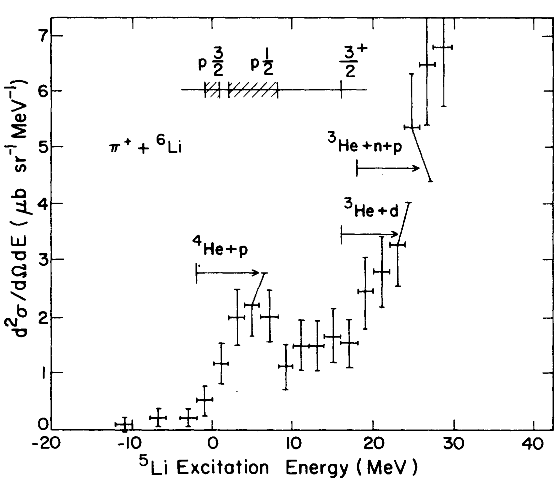

FIG. 7. Excitation energy spectrum for ^{5}Li taken at an apparatus setting of 53°.

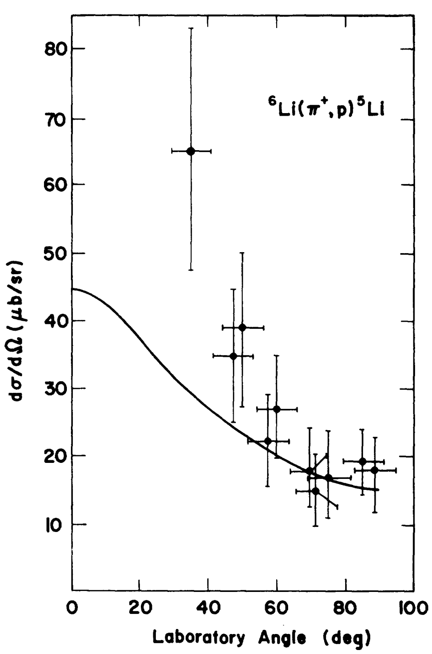

FIG. 8. Differential cross section for the reaction ^{6}Li(π^+, p)^{5}Li obtained by summing over ^{5}Li excitation energies from −5 to 15 MeV. The curve shown is the theoretical cross section calculated by Wienke (Ref. 18) for 70-MeV pions.

by detailed balance from the theoretical results of Ref. 6 for the $^{11}C(\pi^+, p)^{12}C$(g.s.) reaction at E_p = 215 MeV. A two-nucleon absorption mechanism was used by the authors of Ref. 6.

Figure 6 shows that for the most part existing theoretical predictions fail to agree with our experimental results. In particular, our data are not in agreement with the curve of RK, even though their theoretical results were normalized to fit the (p, π^+) cross-section data. The apparent agreement with the calculation of Eisenberg and Letourneux may be fortuitous because their calculated cross sections are extremely sensitive to the harmonic-oscillator parameters used to represent the neutron-hole state.

B. ^{6}Li

In this section results obtained from the $^6Li(\pi^+, p)^5Li$ reaction are presented. The events have been corrected for spark chamber and vertex reconstruction efficiencies and for interactions in the NaI crystal in a manner similar to those of the previous section. Cross sections for this reaction were measured for πp angles within the range from 33 to 90°. Figure 7 shows the ^{5}Li excitation energy spectrum for events taken at an apparatus setting of 53°. Evident in the spectrum is a peak centered between 4 and 5 MeV. The uncertainty in the absolute energy scale of the NaI detector caused by any nonlinearity in the extrapolation from the calibration proton energy of 110 MeV to the proton energies obtained in the $^6Li(\pi^+, p)$ reaction, which were greater than 165 MeV, prevent an exact determination of the ^{5}Li state to which this peak may correspond. However, since the width of the peak is approximately 6 MeV, which is twice our experimental resolution of 3 MeV, we interpret it as arising from absorption leading to contributions from the $p_{3/2}$ ground state and the broad unbound $p_{1/2}$ state of ^{5}Li which occurs at approximately 4 MeV.

Thresholds for various background reactions are also shown in Fig. 7. The threshold for decay of ^{5}Li into a proton and ^{4}He is approximately −1.5 MeV. Hence, it is possible for events from the $^6Li(\pi^+, pp)^4He$ reaction to occur at all energies in the excitation energy spectrum of ^{5}Li. Subtraction of such (π^+, pp) events is not possible without a corresponding background measurement. Instead we have made a background calculation by assuming that (π^+, pp) events which lead to the ^{4}He ground state are described by a pole mechanism which relates the (π^+, pp) cross section to the cross section for π^+ absorption on a free deuteron.[16, 17] This calculation indicated that the background cross section is negligible in the region of interest.

The dependence of the measured cross section on the πp laboratory angle $\theta_{\pi p}$ is shown in Fig. 8. The cross section was obtained by integrating events in the excitation energy range from −5 to 15 MeV. The errors quoted are a combination of statistical errors, uncertainties in efficiencies used to correct the data, and the uncertainty in the energy precision. The cross section decreases rapidly with angle for angles less than 60°. For larger angles the cross section is fairly constant in the measured range up to 90°. The curve shown in Fig. 8 is the result of a calculation by Wienke[18] for the $^6Li(\pi^+, p)$ reaction at T_π = 70 MeV. The calculation is similar to that described in Sec. IV A for the $^{12}C(\pi^+, p)$ process except pure harmonic-oscillator wave functions were used for the s- and p-shell nucleons. The inclusion of pion-rescattering terms prevents the cross section from falling so rapidly with angle and momentum transfer. This is in general agreement with the observed plateau at backward angles (>60°) in the measured cross sections.

V. DISCUSSION AND CONCLUSIONS

The cross sections obtained for the (π^+, p) process are seen to vary widely within the group of nuclei examined in this experiment. Existing theoretical calculations using plane waves indicate that the cross section for the (π^+, p) reaction on ^{12}C and ^{16}O should have the same magnitude.[1, 3] Our measurements show that the ^{12}C cross section is about an order of magnitude higher than the ^{16}O cross section.

The experimental results obtained for the $^{12}C(\pi^+, p)^{11}C$ reaction are lower than most theoretical calculations for this process. Attempts to treat this reaction through the use of optical model wave functions for the pion and proton led to an even poorer agreement with experimental measurements. Perhaps this indicates that optical model wave functions obtained from elastic scattering are not suitable for calculations of a process which occurs far off the mass shell.

The general disagreement between theory and experiment may also indicate a breakdown of the perturbation-theory techniques used in the calculation of this reaction. However, better agreement might be obtained if nuclear models which include a more realistic ground-state description are used, and if effects such as initial-state correlations are included in the theoretical calculations. In any case, the experimental results presented here suggest that nuclear-structure effects play an important role in the (π^+, p) reactions.

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