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Positive pion production from the bombardment of ^{10}B, ^{12}C, ^{16}O, and ^{40}Ca with 147- to 159-MeV polarized protons

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Differential cross sections and analyzing powers for the $(\vec{p},\pi^+)$ reaction have been measured with 147- to 159-MeV polarized protons. Transitions to the ground, 2.12-, and 4.45-MeV states in ^{11}B, the ground, 3.09-, and (3.68-3.85)-MeV doublet in ^{13}C, the ground and 0.87-MeV state in ^{17}O, and the ground state in ^{41}Ca are studied. Pion center-of-mass energies range from 5 to 11 MeV. The results show distinct differences of the $(\vec{p},\pi^+)$ analyzing power for the various transitions.

[NUCLEAR REACTIONS ^{10}B, ^{12}C, ^{16}O, ^{40}Ca$(\vec{p},\pi^+)$, polarized protons, $E_p = 147-159$ MeV; measured $\sigma(\theta)$, $A(\theta)$.]

I. INTRODUCTION

Interest in the $A(p,\pi^+)A+1$ reaction stems from the expected relationship of this process to general questions posed in intermediate energy nuclear physics, such as the nature of meson-nucleus interactions and the importance of mesonic and isobaric degrees of freedom in nuclei. In addition, we still hope that once the mechanism is understood, the (p,π) reaction may become a useful and unique probe of nuclear structure. In the past, there has been considerable experimental and theoretical effort devoted to the study of pion production, as is summarized in recent review articles by Hoistad,[1] Measday and Miller,[2] and Fearing.[3]

Despite the availability of substantial experimental cross section systematics, considerable uncertainty regarding the reaction mechanism still remains. Theoretical calculations based on a pionic-stripping distorted wave model[4,5] (DWBA), a two-nucleon model[6,7] (TNM) including intermediate Δ production, and a pionic knockout[8] model have been only qualitatively successful in describing the cross section data. In some cases, the various model calculations have given similar results, even while using different assumptions about the pion production vertex operator, the distortion in both entrance and exit channels, and the residual-state nuclear wave functions at high momentum transfer. Since this may indicate that cross section measurements alone will not be sufficient to distinguish among different models, analyzing power measurements, which presumably are sensitive in a different way to details of the reaction mechanism,[3] have been carried out to provide additional constraints.

The (p,π^+) reaction was first observed[9] with polarized protons at 206 MeV proton energy. Analyzing powers were measured for ^{12}C(p,π^+) and ^{27}Al(p,π^+) at three angles, but only pions above the $(p,\pi N)$ threshold were included. Pion production leading to discrete low-lying residual states first was investigated[10] for the ^{9}Be$(\vec{p},\pi^+)^{10}$Be and ^{12}C$(\vec{p},\pi^+)^{13}$C reactions at 200-MeV bombarding energy. The measured analyzing power angular distributions show a remarkable similarity: $A(\theta)$ is negative at all angles with a maximum value of about -0.8 at $\theta = 60°$. In addition, the $A(\theta)$ in pion production from nuclei is similar to $A(\theta)$ in the "elementary" process, the $p(\vec{p},\pi^+)d$ reaction.[11] These results suggest[10] that the $(\vec{p},\pi^+)$ analyzing power may be determined primarily by channel distortions or features of the reaction mechanism rather than by the structure of the nuclei involved. Theoretical calculations using the DWBA[5,12-14] have not been able to reproduce these data. Generally, the DWBA calculations yield negative analyzing powers in the forward hemisphere, but often show a strong state dependence of both the overall magnitude and the shape of the angular distribution. On the other hand, preliminary results of the pionic knockout model[8] agree qualitatively with $A(\theta)$ for $^{12}C(\vec{p},\pi^+)$ at 200 MeV.[10]

Since only three final states (the ^{10}Be g.s., 3.37-MeV state, and ^{13}C g.s.), were resolved in the above mentioned experiment by Auld *et al.*,[10] more data for a wider variety of residual states are needed to establish whether the analyzing power in (p,π^+) depends on nuclear structure properties in a systematic way. In the present study, we have measured near threshold ($T_\pi^{\mathrm{c.m.}} \leq 12$ MeV) differential cross sections and analyzing powers of the $(\vec{p},\pi^+)$ reaction for transitions to several final states in ^{11}B, ^{13}C, ^{17}O, and ^{41}Ca.

The procedure used in the present experiment is described in Sec. II. The experimental results are presented in Sec. III, and discussed in comparison with previous measurements and theoretical calculations in Sec. IV. Preliminary results of these measurements have been reported previously.[15]

II. EXPERIMENTAL PROCEDURE

The present analyzing power measurements were made at the Indiana University Cyclotron Facility (IUCF). The beam energies, targets, and target thicknesses employed are listed in Table I. Beam energies were chosen so that the pion center-of-mass energies ranged between 5 and 10 MeV and, in some cases, overlapped earlier IUCF differential cross section measurements with an unpolarized beam. The thickness for each target was selected to optimize event rate and energy resolution.

The low-energy (5- to 10-MeV) pions were detected with the aid of a nondispersive double focusing opposing dipole ($D\bar{D}$) magnetic spectrometer,[16] followed by a detector telescope. The instrument has an image size compatible with commercially available, thick (~ 5000 μm) silicon surface barrier detectors, a 3.5 msr maximum solid angle, a flight path of 77 cm, and a large momentum acceptance (1.5:1, using a 100 mm^2 detector). The entire spectrometer was designed to fit inside the IUCF 163-cm diameter scattering chamber and can operate over an angular range of 17° through 160°. For this measurement, the $D\bar{D}$ detector stack was composed of four elements, namely: (i) a 76-μm Al absorber, which typically reduced count rates in the next element by a factor of 5 with only a moderate reduction in the pion energy (~ 280 keV for a 5-MeV pion); (ii) a 250-μm NE102 plastic scintillator, which established the timing of the event relative to the cyclotron rf beam burst and also provided a ΔE signal; (iii) a 5000-μm Si surface barrier detector which was used to stop the pion and determine its energy; and (iv) a 500-μm Si detector, which acted as a veto. The shape of the pulse produced in the stopping detector and observation of the decay muon provided two additional constraints for pion identification. Pulse shape discrimination was achieved by measuring the time between the prompt signal from the scintillator and the crossover time of the slow bipolar pulse from the stopping detector amplifier. The decay muons were identified by observing their decay positrons in the Si detector during a period of 0.1 to 10 μsec after the pion event. With all these conditions applied, the background could be reduced to a cross section equivalent of about 1 nb/sr. An example of a pion spectrum obtained with the $D\bar{D}$ spectrometer operated in the configuration described above is displayed in Fig. 1.

During runs, pions were identified on-line by multiparameter computer analysis. In addition, the parameters for every event were recorded on magnetic tape so that the data could be reanalyzed off-line with refined conditions. Details about the reduction and correction of measurements using the $D\bar{D}$ are discussed in Ref. 16.

At each angle, data were accumulated in runs of approximately equal length for the spin alignment axis of the incident beam up or down with respect to the scattering plane. The beam polarization (typically ~ 70%) was determined before and after each run, and periodically during long runs, with a $^4He(\vec{p},p)^4He$ polarimeter located between the injector and main stage cyclotrons. A comparison of $^{12}C(\vec{p},p)$ analyzing powers with established values[17] has shown that no significant change in the beam

TABLE I. Summary of beam energies and targets.

Beam energy (MeV)	Target	Thickness (mg/cm^2)	Enrichment (%)
154.5	^{10}B	34 ± 2	96.2
		61 ± 4	96.2
159	^{12}C	15 ± 2	Natural
		36 ± 2	Natural
		55 ± 1	Natural
157	LiOH	25 ± 2	Natural
		55 ± 3	Natural
147	^{40}Ca	51 ± 1	Natural
		160 ± 4	Natural

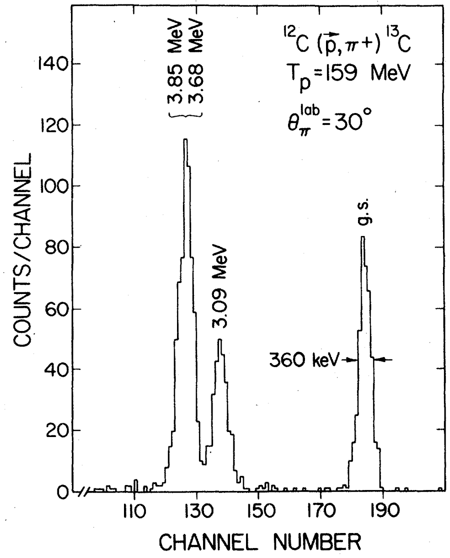

FIG. 1. A $^{12}C(\vec{p},\pi^+)^{13}C$ spectrum obtained with the $D\bar{D}$ spectrometer by bombarding a 55 mg/cm^2 natural carbon target with 159-MeV polarized protons.

polarization occurs during acceleration in the main stage cyclotron.

The absolute normalization of the measured cross sections was calculated from the target thickness, integrated beam current, and various pion detection efficiency corrections. Dead time corrections (typically less than 3%) were determined by pulsing the preamplifiers of the Si detectors and the fast discriminator of the ΔE scintillator at a rate proportional to the beam current and processing these signals in the same manner as those which occurred in the detectors.

The number of angles measured and the statistical accuracy of the data was dictated by the available beam time and beam intensities ($\leq$ 30 nA) and the respective cross sections (between 7 and 400 nb/sr).

III. RESULTS

The results of the present experiment include cross sections and analyzing powers for (p,π^+) transitions to the ground, 2.12-, and 4.45-MeV states in ^{11}B, the ground, 3.09-, and (3.68-3.85)-MeV doublet states in ^{13}C, the ground and 0.87-MeV states in ^{17}O, and the ground state of ^{41}Ca. Measurements were obtained at angles ranging from 30° to 150° in the laboratory.

The results are shown in Figs. 2—4, where the differential cross section $d\sigma/d\Omega$ and the analyzing

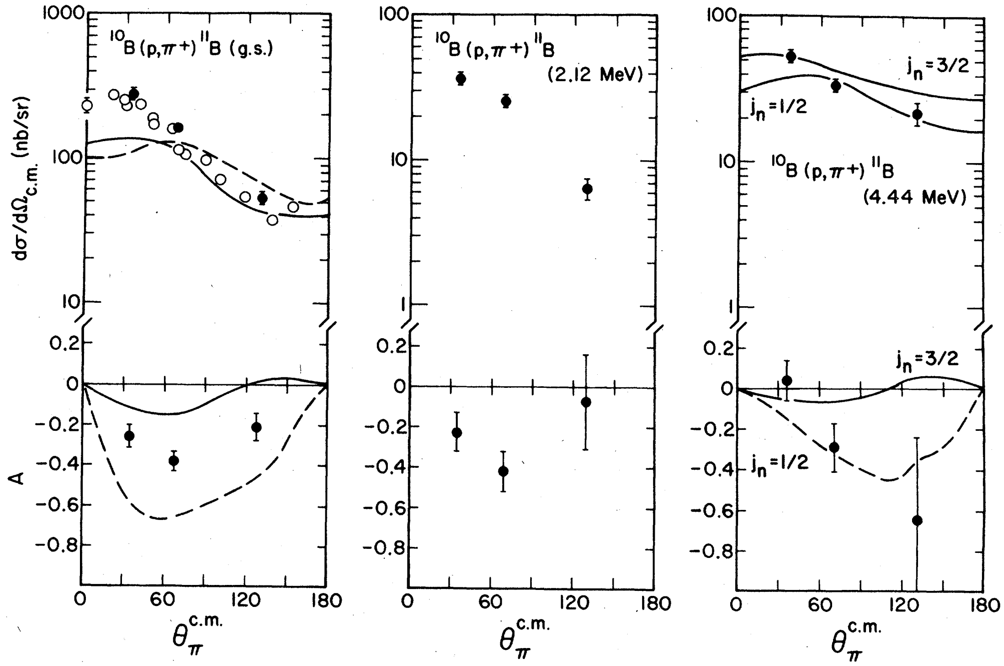

FIG. 2. Differential cross sections and analyzing powers for the $^{10}B(\vec{p},\pi^+)^{11}B$ reaction at 154-MeV bombarding energy as a function of the pion center-of-mass angle $\theta_\pi^{c.m.}$ (solid circles). Earlier measurements at the the same bombarding energy (Ref. 18) are included as open circles. The curves are the results of pionic stripping DWBA calculations (Ref. 5). Solid and dashed curves correspond to different assumptions about the production vertex as explained in the text. The assumed angular momentum of the transfered neutron is denoted by j_n.

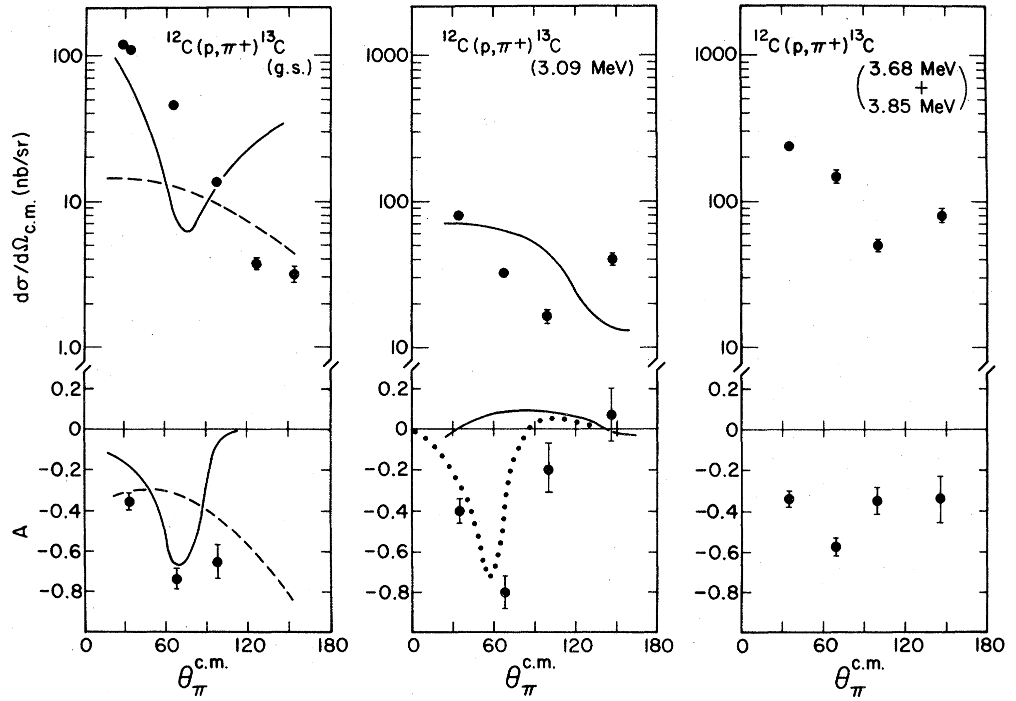

FIG. 3. Differential cross sections and analyzing powers for the $^{12}C(\vec{p},\pi^+)^{13}C$ reaction at 159-MeV bombarding energy. The solid and dashed curves are as described in the caption for Fig. 2. The dotted curve is the result of the pionic knockout model (Ref. 8).

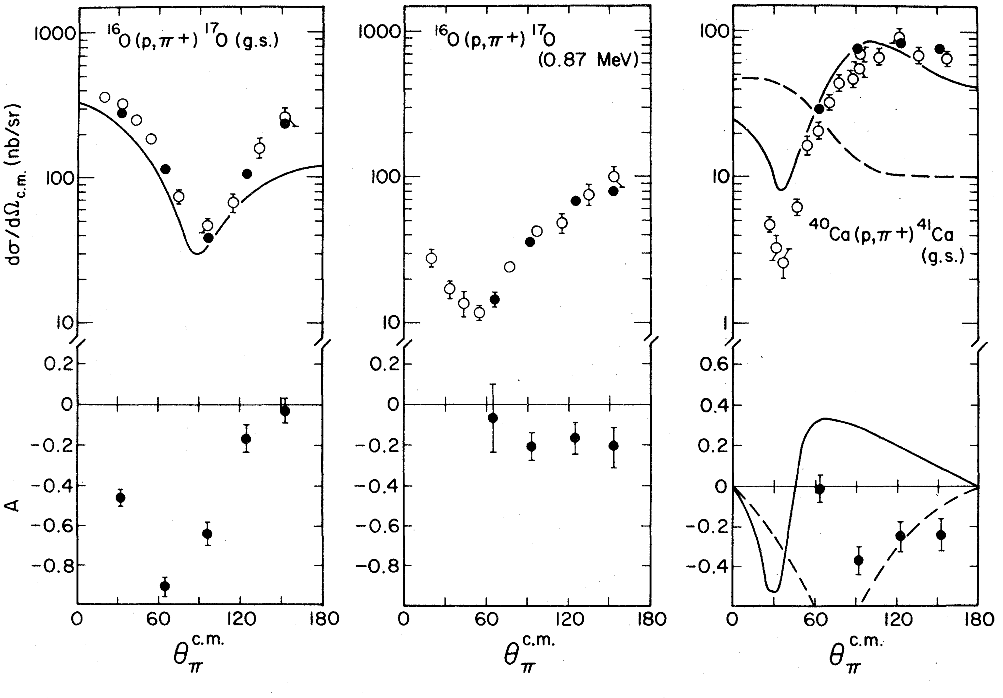

FIG. 4. Differential cross sections and analyzing powers for the $^{16}O(\vec{p},\pi^+)^{17}O$ reaction at 157-MeV bombarding energy and the $^{40}Ca(\vec{p},\pi^+)^{41}Ca$ reaction at 147 MeV (solid circles). Earlier measurements (Refs. 18 and 19) at 157 and 148 MeV bombarding energy for ^{16}O and ^{40}Ca, respectively, are included as open circles. The curves are as described in the caption for Fig. 2.

power $A(\theta)$ are displayed as a function of the pion center-of-mass angle θ. Also shown in Figs. 2 and 4 (denoted by open circles) are $^{10}B(p,\pi^+)$ $^{11}B_{g.s}$ and $^{40}Ca(p,\pi^+)^{41}Ca_{g.s.}$ differential cross sections measured at 154- and 148-MeV bombarding energies, respectively, and $^{16}O(p,\pi^+)^{17}O$ differential cross sections for transitions to the ground state and the 0.87-MeV state.[19]

The error bars of the displayed cross section data include statistical errors and an uncertainty in the subtraction of background. The absolute cross sections are subject to an overall normalization error of ± 20%, which includes uncertainties in beam integration, target thickness, and various corrections for the pion detection efficiency.[16]

The analyzing power was determined from the spin up and down yields and the respective beam polarizations in the usual way (see, e.g., Ref. 20) with the choice of a coordinate system consistent with the Madison Convention.[21] The errors for the analyzing power indicated in Figs. 2–4 are statistical only. The uncertainty in the beam polarization was always less than ± 0.03. A list of the numerical values of the data is available on request from the Indiana University Cyclotron Facility.

IV. DISCUSSION

This measurement provides us, for the first time, with analyzing power distributions for $(\vec{p},\pi^+)$ reactions involving a reasonably large number of transitions to different residual nuclear states. It is natural to pose the question of whether any simple systematic trends can be observed in $A(\theta)$ regarding the dependence of the reaction on the bombarding energy or the excitation energy and quantum numbers of the final state.

Experimental information on the energy dependence of $(\vec{p},\pi^+)$ analyzing powers can be obtained from a comparison of the present $T_p = 159$ MeV measurements for the $^{12}C(\vec{p},\pi^+)^{13}C$ reaction with those obtained[10] at $T_p = 200$ MeV. This comparison covers a range of pion energies from 10 to 40 MeV. For the ground state transition the two sets of analyzing powers agree within experimental errors. The same is true for the sum of the 3.09-3.68-3.85 MeV states, which were not resolved in the 200-MeV measurements.[10] This finding suggests, at least for these two investigated cases, that there is little energy dependence of $A(\theta)$ for the (p,π^+) reaction in the first 40 MeV above threshold.

From the previously available measurements at 200 MeV,[10] we would have concluded that (p,π^+) analyzing powers are also only weakly dependent on the parameters of the specific transition involved, since for several transitions $A(\theta)$ distributions were found to be remarkably similar. The present measurements, however, include a much larger sample of cases and indicate that there is indeed a pronounced transition dependence of $A(\theta)$. It has been suggested earlier[22] that in order to emphasize this dependence, one may choose to represent the $A(\theta)$ distribution data in the following way. As a consequence of a partial wave expansion of the reaction amplitude with respect to the angular momentum l_π of the outgoing pion, one knows (e.g., see Ref. 23) that

$$A(\theta)\frac{d\sigma}{d\Omega}(\theta)(\sin\theta)^{-1} = \sum_{k=0}^{2L-1} \beta_k(\cos\theta)^k , \qquad (1)$$

where L is the maximum angular momentum of the outgoing pion. For all transitions investigated in the present work, the experimental quantity on the left of Eq. (1) is displayed in Fig. 5 as a function of $\cos\theta$. One immediate benefit of this representation of the data is that, e.g., from a linear dependence on $\cos\theta$ we can directly conclude that contributions of pion partial waves with $l_\pi > 1$ are negligible. This seems to be the case for five transitions in the lighter two nuclei as displayed in Fig. 5.

More importantly, however, inspection of Fig. 5 shows that there is a distinct dependence of $A(\theta)d\sigma(\theta)/d\Omega$ on the specifics of the transition. The measured ^{11}B distributions are different from each other, as are those for ^{17}O, and the shape of the ^{41}Ca distribution is unique. On the other hand, the data for the three ^{13}C transitions are similar to each other.

An attempt to correlate these characteristic differences in a *simple* way with the properties of the nuclei involved seems to fail. There is clearly no systematic dependence on spin, parity, or excitation of the final nucleus. Also the shell structure does not seem to be the determining factor, as is seen from a comparison of the 3.09-MeV state in ^{13}C with the 0.87-MeV state in ^{17}O; both of these are known to be predominantly single particle excitations involving the $2s_{1/2}$ neutron orbital,[24] but exhibit completely different angular distributions for $A(\theta)d\sigma(\theta)/d\Omega$.

Since a simple systematic behavior is not revealed by an examination of the data, our only hope to obtain physics information from the (p,π) reaction must lie in detailed theoretical models of the process. Although there has been a considerable amount of theoretical work on pion production, only a few calculations of analyzing powers have

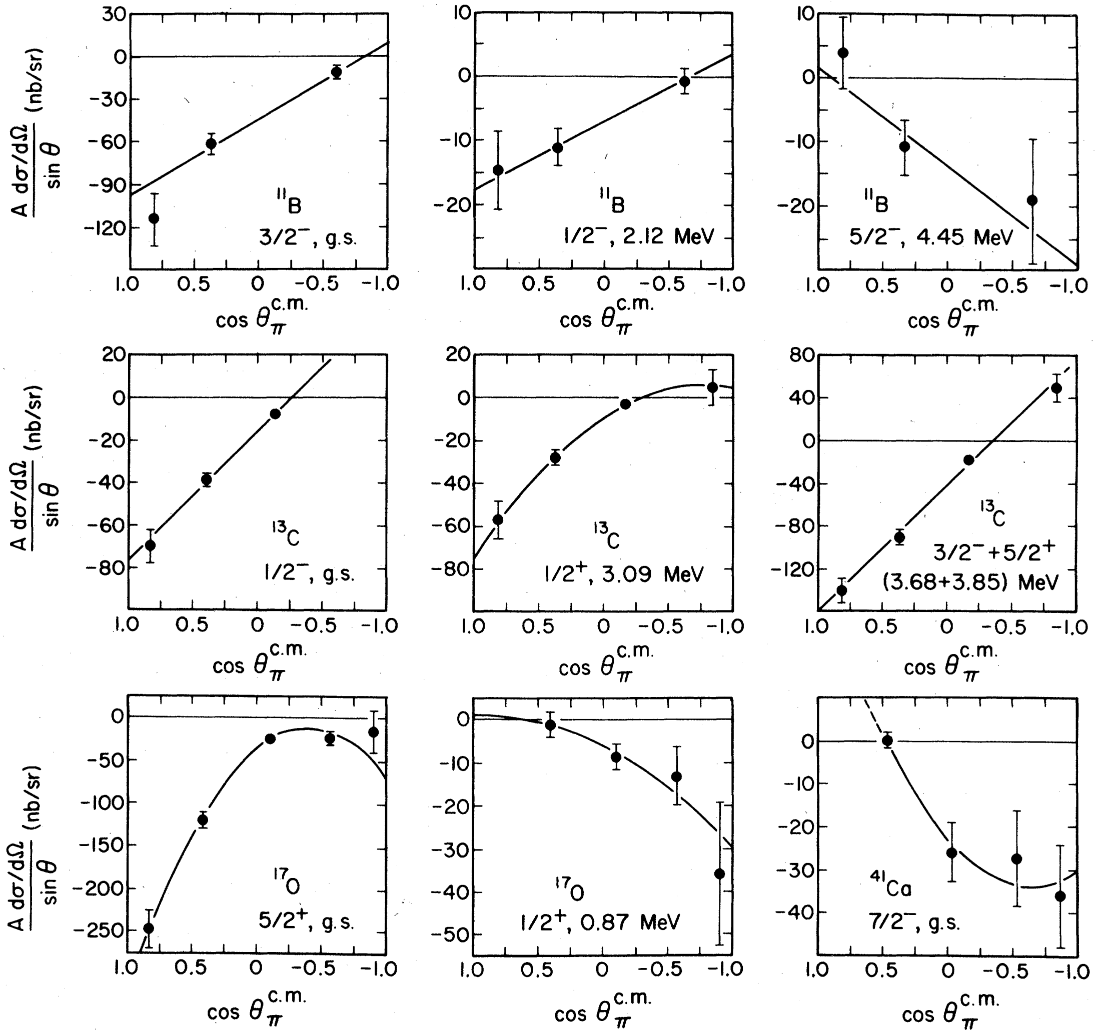

FIG. 5. The experimental values of $A(\theta)d\sigma(\theta)/d\Omega(\sin\theta)^{-1}$ displayed as a function of $\cos\theta$, demonstrating the transition dependence of the analyzing power measurements presented in this paper. The curves are linear or quadratic fits to the points.

been made, and those mostly in the framework of the distorted wave Born approximation formalism.[5,12–14] Analyzing powers obtained within the DWBA model are sensitive to the details of the distorting potentials, since in the *plane wave* Born approximation for pionic stripping, the analyzing power vanishes.[5] These effects have been investigated using different distorting potentials. In most DWBA calculations the static form of the pion production operator is used, but in two cases[5,13] the Galilean invariant form was also investigated (see below).

The earliest DWBA pionic-stripping analyzing power calculation was made by Noble,[12] who included distributions for protons, but not for pions. His calculations gave a large negative analyzing power for the 3.85-MeV state in ^{13}C; the prediction for the ground state was negative but too small in magnitude. A different approach was taken by Young and Gibbs,[13] who included distortions for pions but not for protons. Their calculation leads to a small negative analyzing power for the ^{13}C ground state, but positive values for the 3.09- and 3.85-MeV states in ^{13}C and the ground state in ^{17}O, opposite in sign to what is observed experimentally. Calculations including both proton and pion distortions,[14] the latter by means of an approximate method, yielded negative analyzing powers for the ^{13}C states, but with angular distributions having much more structure than the experimental distributions. Recently, Tsangarides[5] has performed extensive DWBA calculations using the pionic stripping model including realistic pion and proton distortions. He has calculated analyzing powers for transitions corresponding to the previously measured 200 MeV data,[10] as well as for some of the transitions presented in this paper, which are displayed in Figs. 2–4. The Galilean invariant and the static form for the production operator have been used to obtain the solid and dashed set of curves, respectively. Generally, the calculated analyzing powers are negative, but detailed fits are not achieved and the model does not explain even gross features of the cross section and the analyzing power simultaneously, even though in some cases ($^{11}B_{g.s.}$, $^{13}C_{g.s.}$) the calculated cross section has been arbitrarily normalized, and the radius and diffuseness parameters of the binding potential (Woods-Saxon) for the captured neutron were varied freely (within a narrow range around $r_n = 1.18$ and $a_n = 0.5$ fm) to improve agreement with the data. In summary, the DWBA calculations suffer from an extreme sensitivity to the input parameters and, so far, have not yielded a satisfactory explanation of the data.

The only existing analyzing power calculations in a different theoretical framework have been carried out by Gibbs.[8] In his model a virtual pion of the nuclear field is rescattered from the incoming proton. The pion-nucleon amplitude is treated in the distorted wave impulse approximation. In the preliminary calculations, reported in Ref. 8, only s-wave pions were included. These calculations, an example of which is displayed as a dotted line in Fig. 3, reproduce qualitatively the observed negative analyzing powers and some features of the cross section systematics.

So far, no $(\vec{p},\pi)$ analyzing powers have been calculated within the TNM. Such calculations are a most important theoretical task for the future. Of particular interest would be a TNM calculation of $A(\theta)$ for the transitions to the single particle states at 3.09 MeV in ^{13}C and at 0.87 MeV in ^{17}O. The completely different analyzing power angular distribution observed in the two cases suggests that the core nucleons play an important role in pion production.

V. CONCLUSIONS

Cross section and analyzing power angular distributions for the $(\vec{p},\pi^+)$ reaction have been measured near production threshold with 147–149 MeV polarized protons. Several low-lying residual states in ^{11}B, ^{13}C, ^{17}O, and ^{41}Ca have been studied. Comparison of the present results with 200-MeV $^{12}C(\vec{p},\pi^+)^{13}C$ measurements[10] indicates little or no change in the analyzing power distributions over a pion energy range of 10–40 MeV. The present results substantially increase the variety of residual nuclear states for which polarizaton data exist. Contrary to previous work, several cases studied here show a distinct transition dependence of the $(\vec{p},\pi^+)$ analyzing power distributions. Of particular interest are two $2s_{1/2}$ single particle states at 3.09- and 0.87-MeV in ^{13}C and ^{17}O, respectively, which show distinctly different analyzing power distributions.

Calculations of $(\vec{p},\pi^+)$ analyzing powers have so far been performed employing the DWBA (pionic stripping) model[5,12–14] and a pionic knockout model.[8] In general, these calculations are quite sensitive to the input parameters, and do not describe well both the cross section and analyzing power data simultaneously. Two-nucleon model calculations are needed to shed light on the question of whether analyzing power data for (p,π) will be helpful in establishing the dominant production mechanism.

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