Energy dependence of the analyzing power for the $^{12}C(\vec{p},\pi^+)^{13}C$ reaction with polarized protons of 200 to 250 MeV

G. J. Lolos, P. L. Walden, E. L. Mathie,* G. Jones, and E. G. Auld
Physics Department, University of British Columbia and Tri-University Meson Facility, Vancouver, British Columbia, Canada V6T 2A6

W. R. Falk
Physics Department, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2

R. B. Taylor
Physics Department, James Cook University of North Queensland, Townsville, North Queensland, Australia
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The analyzing power angular distributions $A_y(\theta)$ for the $^{13}C_{g.s.}$ as well as for several $^{13}C^*$ excited state transitions from the $^{12}C(\vec{p},\pi^+)^{13}C$ reaction are reported as a function of incident proton energy from 200 to 250 MeV. For the first time in reactions of the type $A(\vec{p},\pi^+)A+1$, a dramatic energy dependence is observed for the analyzing power. A dependence of the shape of the analyzing power on the nature of the excited nuclear state is also observed. The cross section for the $^{13}C_{g.s.}$ transition shows indication of backward peaking not observed at energies below 225 MeV.

[NUCLEAR REACTIONS $^{12}C(\vec{p},\pi^+)^{13}C_{g.s.}$ and several excited states, polarized protons, $T_p=200-250$ MeV; measured $A_y(\theta)$, $d\sigma/d\Omega(\theta)$.]

Interest in the (p,π) reaction leading to discrete final states of the residual nucleus was spawned by the expectation that such reactions would lead to new information concerning unexplored aspects of nuclear structure (such as the magnitude of the high-momentum components of nuclear wave functions). In addition, the (p,π) reaction spans much of the π nucleus as well as proton-nucleus fields of physics and as such the potential wealth of information that can be extracted is exceeded only by the complication in unraveling the reaction mechanism. Thus far theoretical attempts to describe the pion production mechanism in such reactions using polarized protons have been singularly unsuccessful.[1–3]

The first exclusive pion production measurements with polarized protons were performed at TRIUMF with a 200-MeV incident beam.[4] The reactions investigated were $^9Be(\vec{p},\pi^+)^{10}Be$ and $^{12}C(\vec{p},\pi^+)^{13}C$. The analyzing power angular distribution $A_y(\theta)$ results yielded the surprising fact that for all four discrete states observed ($^{10}Be_{g.s.}$, $^{10}Be^*_{3.37}$, $^{13}C_{g.s.}$, and $^{13}C^*_{(3.09,3.68,3.85)}$) very similar angular distributions resulted. In addition the angular dependence of the $A_y(\theta)$ was remarkably similar to that of the $\vec{p}p\rightarrow d\pi^+$ process for the same pion energies[5] (when appropriate kinematic angle transformations were performed). This similarity implied that the $A_y(\theta)$ depended more on the reaction mechanism involved than on details of nuclear structure. Recent measurements of the $^{12}C(\vec{p},\pi^+)^{13}C$ reaction at $T_p=159$ MeV yielded analyzing power results for transitions leading to $^{13}C_{g.s.}$ as well as the $^{13}C^*_{3.09}$ and $^{13}C_{(3.68,3.85)}$ excited states[6] that were little different from those observed at 200 MeV.[4] Thus no energy dependence (or state dependence for that matter) was observed for the shape of the analyzing power in the 160- to 200-MeV incident proton energy region.

In this Communication the analyzing power for the transitions leading to $^{13}C_{g.s.}$, $^{13}C^*_{(3.09,3.68,3.85)}$, $^{13}C^*_{(6.86,7.50)}$, and $^{13}C^*_{(9.50,9.90)}$ states are presented for the angular range of 46° to 135° in the laboratory. Incident protons of 225 and 250 MeV from the TRIUMF cyclotron were used although some measurements were also obtained at $T_p=200$ MeV as a check of consistency with previous results. Pions were detected by a 65-cm Browne-Buechner magnetic spectrograph in conjunction with three helically wound multiwire proportional chambers (MWPC) for track reconstruction and momentum definition. A three-scintillator telescope, used as a fast trigger, helped to provide event definition as well as time of flight. Pions were identified on the basis of energy loss, time of flight, and track definition. The total background not associated with pions was less than 15 pb/MeV sr at 250 MeV decreasing to less than 2 pb/MeV sr at 200 MeV.

The analyzing power $A_y(\theta)$ and the spin-averaged (unpolarized) differential cross section $d\sigma/d\Omega$ have been calculated using the relations

$$A_y(\theta)=\frac{d\sigma(\uparrow)/d\Omega-d\sigma(\downarrow)/d\Omega}{P(\downarrow)d\sigma(\uparrow)/d\Omega+P(\uparrow)d\sigma(\downarrow)/d\Omega}$$

and

$$\frac{d\sigma}{d\Omega}(\theta)=\frac{P(\uparrow)d\sigma(\downarrow)/d\Omega+P(\downarrow)d\sigma(\uparrow)/d\Omega}{P(\downarrow)+P(\uparrow)}$$

where P and $d\sigma/d\Omega$ are the magnitudes of the beam polarization and differential cross section, respectively. The arrows indicate the spin direction according to the Madison convention.[7]

The energy dependence of the $A_y(\theta)$ for the $^{13}C_{g.s.}$ is shown in Fig. 1. The analyzing power angular distribution $A_y(\theta)$ exhibits a dramatic dependence on incident proton energy in the region between 200 and 225 MeV. This is the first time that such a significant variation with incident proton energy has been observed. Considering the fact that the $A_y(\theta)$ for the $^{13}C_{g.s.}$ transition appears similar at 159 and 200 MeV, the rapid change seen here is the more surprising. All the results for 225 and 250 MeV are a combination of two separate experiments. The solid points represent the most recent results with improved timing and energy resolution, as well as statistics, whereas the earlier data are represented by crosses.[8] The two results are in good agreement and combined they present a more complete picture of the overall effect.

Our overall resolution did not allow us to separate the 3.09-, 3.68-, and 3.85-MeV excited states, but nevertheless this group of three states also shows a significant dependence on incident proton energy (primarily in the energy range between 200 and 225 MeV) as shown in Fig. 2. Although the measured analyzing power for the $^{13}C^*_{3.09}$ and $^{13}C^*_{(3.68,3.85)}$ states at $T_p=159$ MeV are not as complete as one would like,[6] they appear to be rather similar to that measured for the $^{13}C^*_{(3.09,3.68,3.85)}$ combined state at 200 MeV.[4] In fact the overall angular dependence for the $^{13}C_{g.s.}$ and the group of states between 3 and 4 MeV is quite similar, for protons of 200 to 225 MeV, as is the shift of the maximum for the $A_y(\theta)$ toward the smaller angles between 225 and 250 MeV.

For the other two groups of states, $^{13}C^*_{(6.86,7.50)}$ and $^{13}C^*_{(9.50,9.90)}$, no $A_y(\theta)$ data exist below 200 MeV and neither state shows any large qualitative (shape) dependence on incident proton energy, at least not between 225 and 250 MeV. The two states do, however, exhibit markedly different analyzing power angular distributions $A_y(\theta)$, as shown in Figs. 3 and 4. We believe that $^{13}C^*_{(9.50,9.90)}$ is almost exclusively populated by the $^{13}C^*_{9.50}$ state since the $^{13}C^*_{9.90}$ has been shown to be very weakly populated by the (p,π^+) reaction at lower pion energies.[9] Our pion excitation spectra also indicate width and centroid location consistent with a single $^{13}C^*_{9.50}$ transition. The analyzing power for the $^{13}C^*_{9.50}$ transition then is the only state from the $^{12}C(\vec{p},\pi^+)^{13}C$ reaction above 200 MeV which exhibits the large negative asymmetry at $\theta_{lab}\simeq 60°$ with the characteristic oscillatory shape which dominates the picture for all ^{13}C transitions ob-

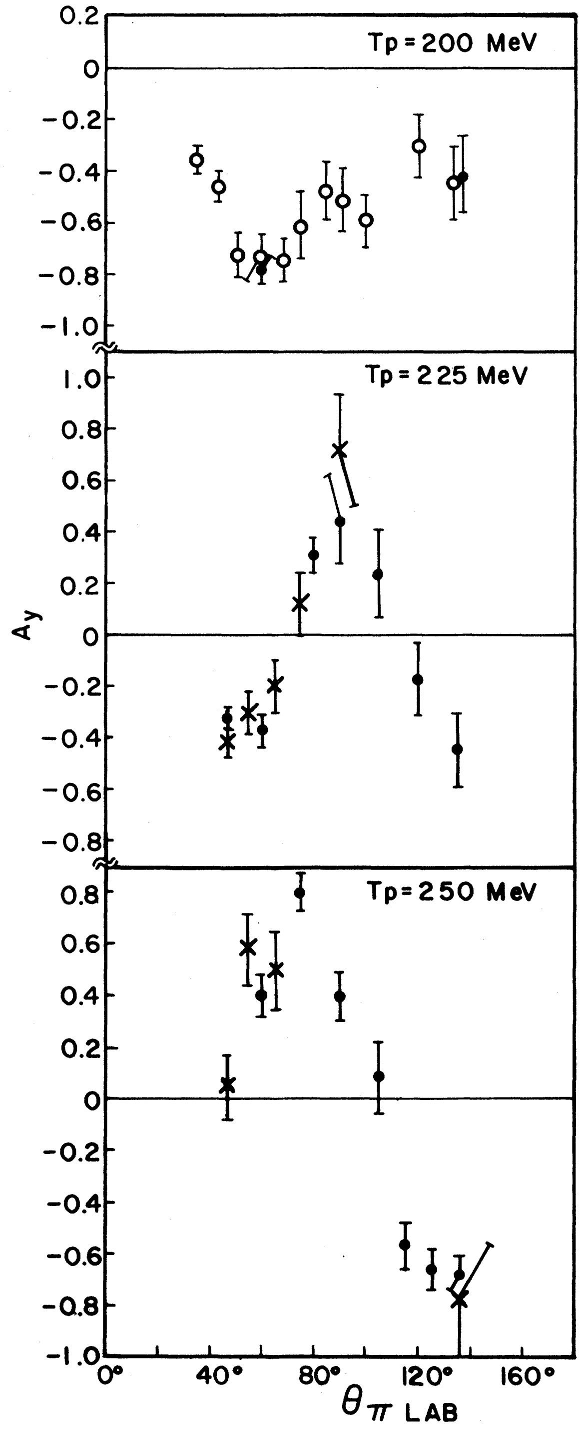

FIG. 1. Analyzing power angular distributions $A_y(\theta)$ for the $^{13}C_{g.s.}$ transition for (a) $T_p=200$ MeV (the solid circles are results from the present work and the open circles are from Ref. 4), (b) $T_p=225$ MeV, and (c) $T_p=250$ MeV. The different symbols are explained in the text. Statistical errors only are indicated.

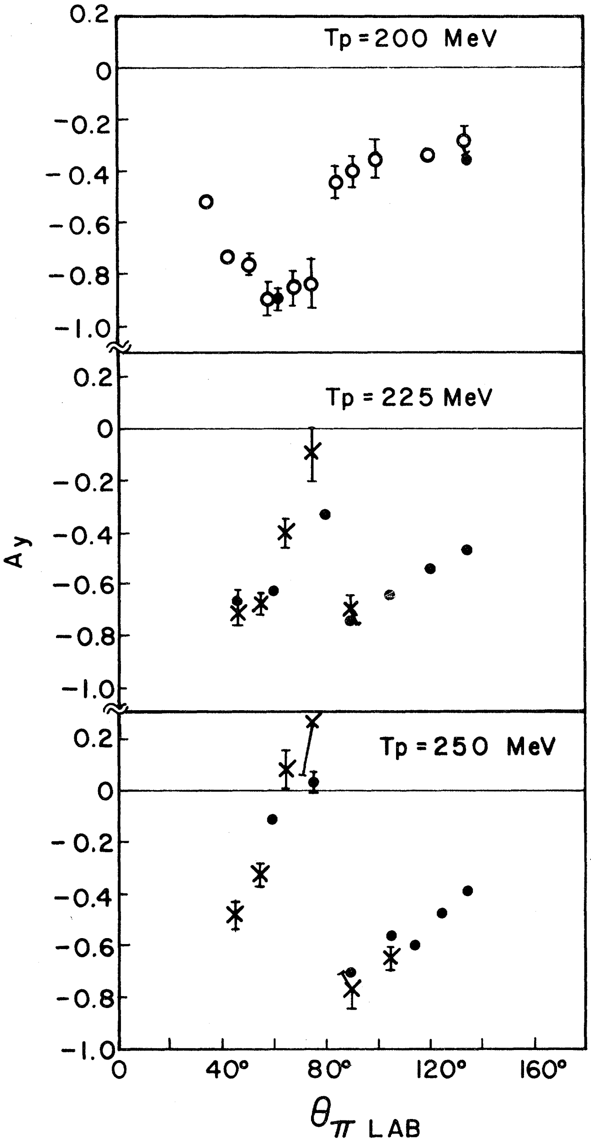

FIG. 2. $A_y(\theta)$ results for the ${}^{13}\mathrm{C}^*_{(3.09,3.68,3.85)}$ transitions for (a) $T_p = 200$ MeV, (b) $T_p = 225$ MeV, and (c) $T_p = 250$ MeV. The open circles in (a) are from Ref. 4. The symbols are explained in the text. Statistical errors only.

served below 200 MeV.

At the present time no coherent picture of the $(\vec{p}, \pi^+)$ reaction exists. The ${}^9\mathrm{Be}(\vec{p}, \pi^+){}^{10}\mathrm{Be}_{\mathrm{g.s.}}$ reaction in the 200–250-MeV range has shown very little energy dependence[8,10] and no consistent trend of dependence on the structure of the nuclear states involved has been seen.[6] In addition the ${}^9\mathrm{Be}(\vec{p}, \pi^-){}^{10}\mathrm{C}_{\mathrm{g.s.}}$ analyzing power $A_y(\theta)$ is very similar[11,12] to the shape shown in Fig. 1 for 225 and 250 MeV although the $(\vec{p}, \pi^-)$ reaction mechanism has traditionally been assumed to be quite different from that of the $(\vec{p}, \pi^-)$ reaction.

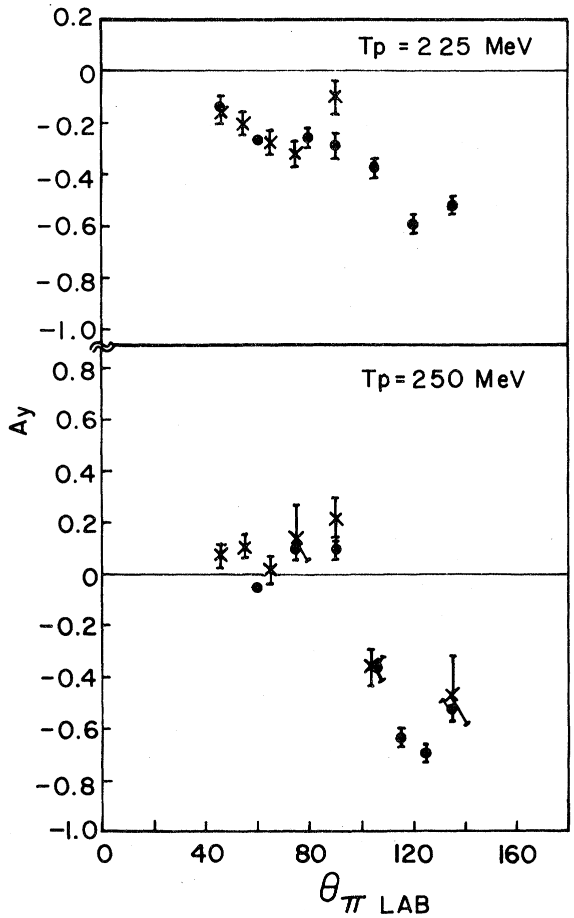

FIG. 3. $A_y(\theta)$ results for the ${}^{13}\mathrm{C}^*_{(7.50,6.86)}$ transitions for (a) $T_p = 225$ MeV, (b) $T_p = 250$ MeV. The symbols are explained in the text. Statistical errors only.

The angular distribution of the (unpolarized) differential cross section for the ${}^{13}\mathrm{C}_{\mathrm{g.s.}}$ is shown in Fig. 5. We see strong evidence for a rising cross section for $\theta_{\mathrm{lab}} > 105°$ with a more pronounced backward peaking at 250 MeV than at 225 MeV. This is the first time a rise in the differential cross section for large angles has been observed for the ${}^{12}\mathrm{C}(\vec{p}, \pi^+){}^{13}\mathrm{C}_{\mathrm{g.s.}}$ reaction. Previous measurements at 159 MeV indicate a continuous, albeit diminishing, drop[6] to $\sim 150°$ while at 200 MeV the cross section flattens out for $\theta_\pi \geq 90°$.[4,13–14]

More data exploring the energy dependence of the cross section and the analyzing power are urgently needed to answer some of the questions raised by this work. Does the $A_y(\theta)$ for the ${}^{13}\mathrm{C}_{\mathrm{g.s.}}$ remain the same between 159 and 200 MeV? The 159-MeV measurements themselves are rather limited.[6] A check at the 180-MeV region would be most useful. Is the dramatic change in $A_y(\theta)$ for both the ${}^{13}\mathrm{C}_{\mathrm{g.s.}}$ and ${}^{13}\mathrm{C}^*_{(3.09,3.68,3.85)}$ transitions between 200 and 225 MeV gradual or very sudden? Here measurements at

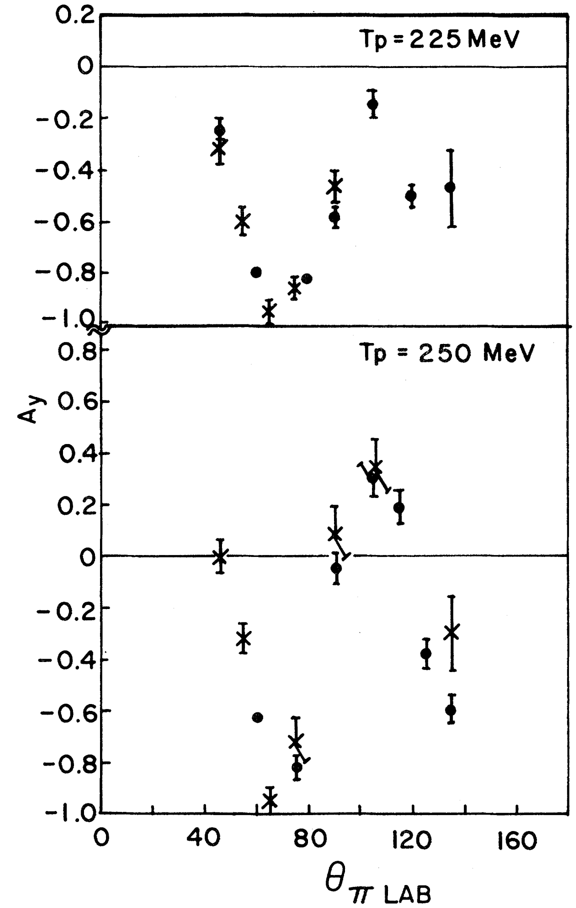

FIG. 4. As in Fig. 3 for the $^{13}C^{*}_{(9.50,9.90)}$ transitions.

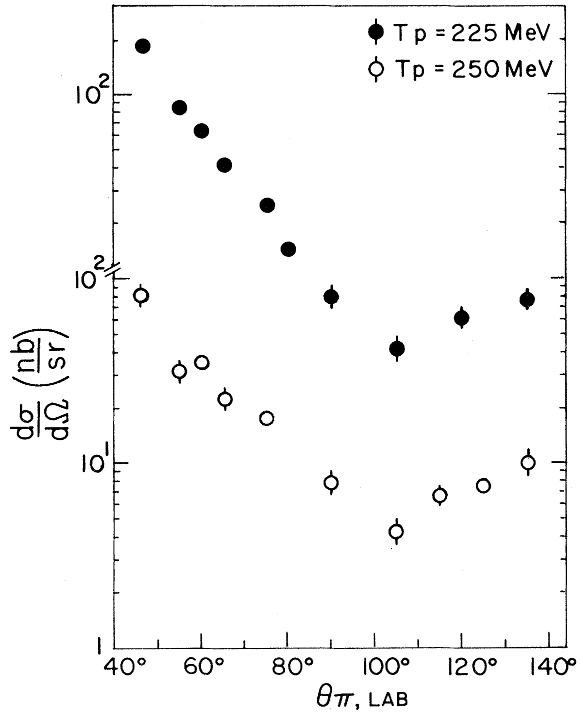

FIG. 5. Unpolarized (spin-averaged) cross section for the $^{13}C_{g.s.}$ for $T_p = 225$ MeV (solid circles) and $T_p = 250$ MeV (open circles). Error bars reflect statistics only. Systematic uncertainties are ~20%.

the region between 200 and 225 MeV would be most welcome. Why is the energy dependence so dramatic in ^{12}C but not in ^{9}Be? All these are questions that have to be answered before one can begin to understand the (p, π^+) reaction mechanism and its systematics.

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*Present address: Schweizerisches Institut für Nuklearforschung, CH-5234 Villigen, Switzerland.

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