^{9}Be($\vec{p}$, π^-)^{10}C reaction in the 200–250 MeV proton energy range

G. J. Lolos, E. L. Mathie,* P. L. Walden, G. Jones, and E. G. Auld
University of British Columbia, Vancouver, British Columbia, Canada V6T 2A6

R. B. Taylor
James Cook University of North Queensland, Townsville, North Queensland, Australia
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Measurements of the dependence on incident proton energy of the analyzing power $A_y(\theta)$ for $\vec{p}\pi^-$ production on nuclei are reported for the ^{9}Be($\vec{p}$, π^-)^{10}C reaction leading to the ground state (g.s.) and the first three excited states of ^{10}C. For the transition to the g.s. the analyzing power shows little dependence on proton energy while for transitions leading to the $^{10}C^*_{3.35}$ and $^{10}C^*_{6.60}$ states it varies considerably with incident proton energy. Nuclear structure dependence of the $A_y(\theta)$ is also observed for the first time in $\vec{p}\pi^-$ reactions.

[NUCLEAR REACTIONS ^{9}Be($\vec{p}$, π^-)^{10}C; measured $A_y(\theta)$ for $^{10}C_{g.s.}$, $^{10}C^*_{3.35}$, $^{10}C^*_{5.28}$ and $^{10}C^*_{6.60}$ transitions; $E_{\vec{p}}=200$, 225, 250 MeV; calculated $Y_0(\theta)$.]

A unique aspect of exclusive pion production (pion production where the residual nucleus is left in a definite state) is the very high momentum transfer characterizing the reaction.[1,2] While the nuclear Fermi momentum is ~ 270 MeV/c, the minimum momentum transfer in a (p,π) reaction is ~ 480 MeV/c. For incident protons of 250 MeV one can reach up to 800 MeV/c of momentum transfer for backward angle pion emission. Since the single-nucleon wave functions drop rapidly with increasing momentum,[3] the large momentum transfer in the exclusive (p,π) reaction accounts for their small cross sections as compared to inclusive (p,π) reactions.

Because of the extremely small cross sections associated with exclusive (p,π^-) reactions where experimental difficulties are compounded by additional factors such as the need for good background rejection and acceptable resolution, little data exist. A characteristic feature of the few (p,π^-) reactions that have been measured is the lack of any significant angular dependence of the differential cross sections.[4–7] In fact, such featureless data have been interpreted as evidence of a multistep production mechanism. The first measurement (inclusive) of the spin dependence of π^- production from nuclei showed a flat and slightly negative analyzing power as a function of kinetic energy,[8] whereas the first analyzing powers reported for the exclusive ^{9}Be($\vec{p}$, π^-)^{10}C(g.s.) reaction, measured at 200, 225, and 250 MeV, indicated a fairly large positive value over most of the large angles of the angular range.[9–11]

In this Communication we report the first measurements of the ^{9}Be($\vec{p}$, π^-)^{10}C reaction leading to states of ^{10}C other than the ground state, as well as the ground state, for incident proton energies of 200, 225, and 250 MeV. Although the ^{9}Be(p, π^-)^{10}C* reaction has been studied at a number of energies before [$T_p=185$ MeV,[5] $T_p=613$ MeV,[12] and $T_p=600$ MeV (Ref. 13)] such earlier work was restricted to the use of unpolarized beam.

Details of the experimental hardware as well as the data acquisition system and analysis techniques will be described in a later publication. In summary, the experimental apparatus involved a 65 cm Browne-Buechner magnetic spectrograph; the detector system consisted of a three-scintillator telescope used as a fast trigger for event definition and three helically wound multiwire proportional chambers (MWPC) for track reconstruction (and thence momentum definition). The data acquisition system consisted of a PDP 11/34 computer with disk, magnetic tape, and graphics peripherals. The spectrometer solid angle (by geometry) is of the order of ~ 3 msr although the effective solid angle depends on incident pion energy. The target thickness was 155 mg/cm^2 of reactor-grade graphite bombarded by average proton beam current of ~ 8 nA. The beam polarization, $\sim 70\%$, as well as the beam current were monitored by a CH_2 polarimeter detecting both the scattered and recoil protons.

The pions were identified on the basis of: energy loss in the scintillators, particle time of flight, and track definition using the MWPC's. The total background not associated with pions was reduced to $< 1\%$ of the total number of pions. The background due to scattered pions as well as decay muons is $\sim 4\%$ of the total number of pions. A characteristic pion excitation spectrum is shown in Fig. 1.

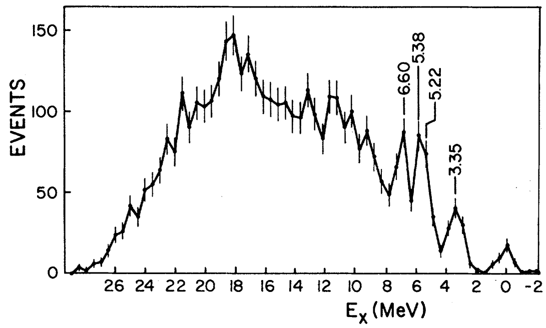

FIG. 1. Pion excitation spectrum for 46° and $T_p = 225$ MeV.

Our results for the analyzing power $A_y(\theta)$ for the (p, π^-) reaction (Figs. 2–5) show striking differences from that of positive pion production at 200 MeV.[14] In the latter ${}^9\mathrm{Be}(\vec{p}, \pi^+){}^{10}\mathrm{Be}$ reaction the $A_y(\theta)$ values for both ${}^{10}\mathrm{Be}$ ground and 3.37 MeV excited states were negative through the whole angular range. At $T_p = 200$ MeV our $(\vec{p}, \pi^-)$ results are restricted to the angular range below $\theta_L = 90°$. The analyzing power to the ground-state transition, however, is in agreement with that reported in Ref. 11 although our

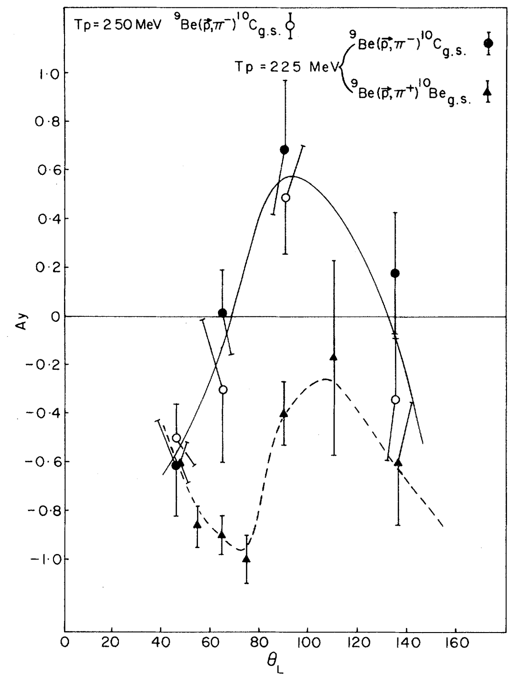

FIG. 3. Analyzing power $A_y(\theta)$ for the ${}^{20}\mathrm{C}$(g.s.) at $T_p = 225$ MeV (solid circles) and $T_p = 250$ MeV (open circles). The triangles are the results for the ${}^9\mathrm{Be}(\vec{p}, \pi^+)$-${}^{10}\mathrm{Be}$(g.s.), also at $T_p = 225$ MeV from Ref. 15. Error bars reflect statistics only. Lines drawn to guide the eye.

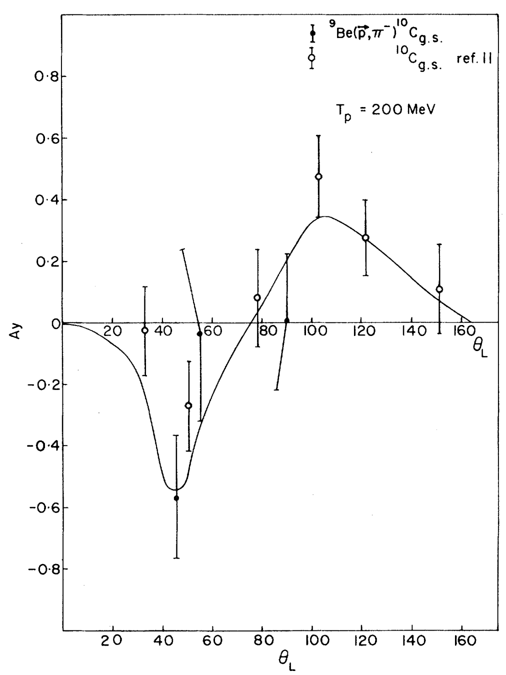

FIG. 2. Results of the analyzing power $A_y(\theta)$ at $T_p = 200$ MeV for the ground state (solid circles) for the ${}^9\mathrm{Be}(\vec{p}, \pi^-){}^{10}\mathrm{C}$ reaction. The open circles are the results in Ref. 11. Error bars reflect statistics only. The solid line is to guide the eye for the ground-state analyzing power.

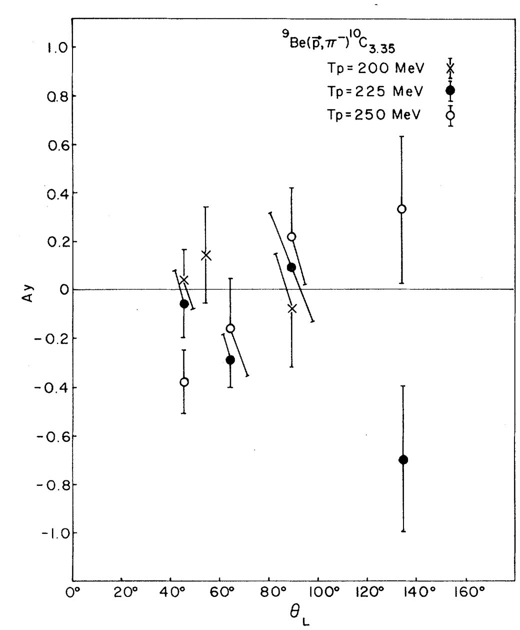

FIG. 4. $A_y(\theta)$ results for the transition to the ${}^{10}\mathrm{C}^*_{3.35}$ for $T_p = 200$ MeV (crosses), $T_p = 225$ MeV (solid circles), and $T_p = 250$ MeV (open circles). Statistical errors only.

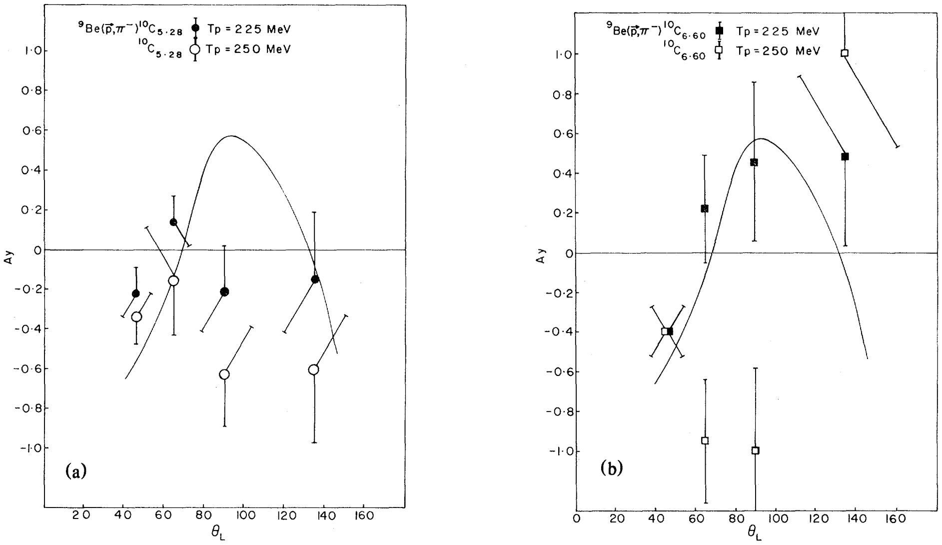

FIG. 5. $A_y(\theta)$ results for (a) the $^{10}C^*_{5.28}$ transition at $T_p = 225$ MeV and $T_p = 250$ MeV, and (b) the $^{10}C^*_{6.60}$ transition at $T_p = 225$ MeV and $T_p = 250$ MeV. For comparison the solid line indicates the ^{10}C(g.s.) dependence at the same energies. Statistical errors only.

results suggest a sharper minimum at $\theta_L = 46°$ than expected from Ref. 11. In fact the shape of the $A_y(\theta)$ at 200 MeV as reported in Ref. 11 with the addition of our 46° analyzing power (Fig. 2) is very similar to those measured by us at $T_p = 225$ and 250 MeV (Fig. 3)[15] implying very little, if any, energy dependence. The two states that do show a dramatic dependence on energy are the $^{10}C^*_{3.35}$ and the $^{10}C^*_{6.60}$ states (Figs. 4 and 5). Interpretation of the analyzing power appropriate to the 5.28 MeV state is complicated by the fact that both 5.22 and 5.38 MeV states contribute.[16] Unfortunately, the theoretical situation regarding the $(\vec{p}, \pi^-)$ reaction is particularly undeveloped. No detailed model calculations exist. Recently a model was proposed assuming pion production by direct knockout from the pionic field in the nucleus.[17] Although this model is still in a preliminary form, it does predict a positive $A_y(\theta)$ for

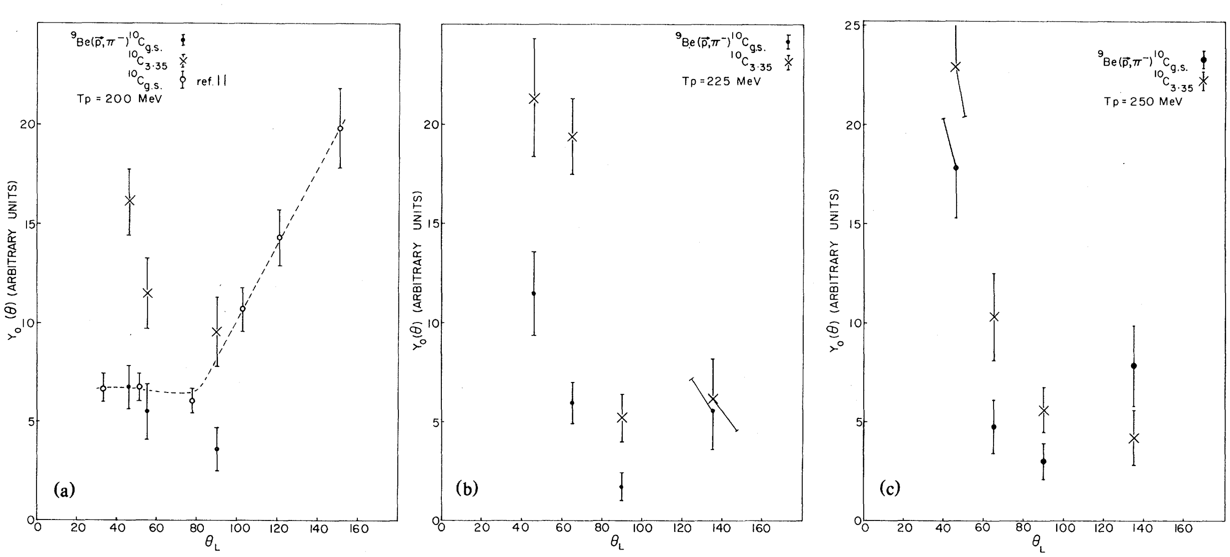

FIG. 6. Spin-averaged yields $Y_0(\theta)$ for the $^9Be(\vec{p}, \pi^-)^{10}C$ leading to the ground state and the $^{10}C^*_{3.35}$ state at (a) $T_p = 200$, (b) 225, and (c) 250 MeV. The $T_p = 200$ MeV cross section for the ^{10}C(g.s.) from Ref. 11 is included for comparison normalized to our 46° yield reported in this paper. Statistical errors only.

ground-state transitions at all pion angles at $T_p = 200$ MeV. The parameters used in the calculations were optimized for ^{12}C but are expected to be similar for light nuclei in general. At its present level the model fails to reflect the negative $A_y(\theta)$ at the forward angles or the differences in energy dependence which we observe for the $(\vec{p}, \pi^-)$ reaction to different excited states. The model is, however, sensitive to nuclear structure and predicts large differences in the $A_y(\theta)$ for different transitions.

The angular distribution $Y_0(\theta)$ of the unpolarized yield for the transition to the 3.35 MeV state in ^{10}C is strongly forward peaked at all proton energies (Fig. 6). We also see evidence for more angular structure in the (unpolarized) differential cross section for the transition to ^{10}C(g.s.) (Fig. 6) than has previously been reported near threshold.[5,11] In this respect, our results are more similar to those measured previously at higher energy.[18] If negative pion production from nuclei arose from a multistep process, as has been previously inferred, one would expect a rather featureless angular distribution for the differential cross section as well as the analyzing power. In light of the significant structure presented here in the angular distributions for both differential cross sections as well as analyzing power, a more fundamental production mechanism (such as that of Gibbs[17]) appears necessary. Clearly, more $(\vec{p}, \pi^-)$ reaction data are required in order to experimentally determine the general features of this pion production reaction near threshold.

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*Present address: Swiss Institute for Nuclear Research, Villigen, Switzerland.

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