Positive pion production from the bombardment of ^{9}Be with 200, 225, and 250 MeV polarized protons

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The analyzing power angular distributions $A_y(\theta)$ for the $^{10}\mathrm{Be}_{\mathrm{g.s.}}$ as well as the $^{10}\mathrm{Be}^{*}_{3.37}$ state transitions from the $^{9}\mathrm{Be}(\vec{p},\pi^{+})^{10}\mathrm{Be}$ reaction are reported as a function of incident proton energy from 200 to 250 MeV. Instead of the dramatic dependence on energy characterizing the $^{12}\mathrm{C}(\vec{p},\pi^{+})^{13}\mathrm{C}$ reaction, the analyzing power for the present reaction shows little variation with energy. At energies above 200 MeV the analyzing power angular distributions exhibited by the $(\vec{p},\pi^{+})$ reactions on ^{9}Be and ^{12}C are markedly different, unlike the earlier observations at 200 MeV where the distribution was essentially the same.

[NUCLEAR REACTIONS $^{9}\mathrm{Be}(\vec{p},\pi^{+})^{10}\mathrm{Be}_{\mathrm{g.s.}}$ and $^{10}\mathrm{Be}^{*}_{3.37}$, polarized protons, $T_p=200-250$ MeV, measured $A_y(\theta)$ for $^{10}\mathrm{Be}_{\mathrm{g.s.}}$ and $^{10}\mathrm{Be}^{*}_{3.37}$ transitions.]

A characteristic feature of exclusive (p,π) reactions on nuclei, reactions in which the incoming nucleon is captured by the target nucleus leaving the resulting nucleus in a coherent final state, is the very large momentum transfer. It was precisely this almost unique characteristic of the exclusive (p,π) reaction that generated the early interest in reactions of this type as a probe of the high momentum components of the nuclear wave function.[1]

The initial results of the dependence of the differential cross section on both the target nucleus (for light nuclei), as well as the details of the final state excited, indicated some common characteristics for final states of $1p$ shell configurations ($^{11}\mathrm{B}_{\mathrm{g.s.}}$, $^{13}\mathrm{C}_{\mathrm{g.s.}}$, and $^{14}\mathrm{C}_{\mathrm{g.s.}}$). The angular distributions of the cross sections were characterized by a monotonically decreasing distribution although the magnitudes of the cross sections varied greatly, while the distributions for final states of $1d_{5/2}$ and $2s_{1/2}$ configurations ($^{17}\mathrm{O}_{\mathrm{g.s.}}$, $^{13}\mathrm{C}_{3.09}$, $^{13}\mathrm{C}_{3.85}$, and $^{17}\mathrm{O}_{0.87}$) were characterized by a minimum at $\sim 70°-90°$ with a rise for both larger and smaller angles.[1] Furthermore, the angular distribution of the differential cross section did not seem to depend much on the incident proton energy, although the magnitude increased with increasing incident energy.[2] These results pointed to a common production mechanism (at least for the light nuclei) and a strong dependence on nuclear structure.[3] In addition, the two most widely used reaction models, the single-nucleon model (SNM) [also referred to as the one-nucleon model (ONM)] and the two-nucleon model (TNM), where tested, both produce acceptable agreement with the available experimental results.[4]

The first exclusive pion production measurements from nuclei using polarized protons were performed at TRIUMF.[5] At an incident proton energy of 200 MeV two reactions were investigated; $^{9}\mathrm{Be}(\vec{p},\pi^{+})^{10}\mathrm{Be}$ and $^{12}\mathrm{C}(\vec{p},\pi^{+})^{13}\mathrm{C}$. The results were surprising in that all four transitions observed ($^{10}\mathrm{Be}_{\mathrm{g.s.}}$, $^{13}\mathrm{C}_{\mathrm{g.s.}}$, $^{10}\mathrm{Be}^{*}_{3.37}$, and $^{13}\mathrm{C}^{*}_{(3-4)\,\mathrm{MeV}}$ group of states) exhibited very similar angular distributions for the analyzing power $A_y(\theta)$. These results not only indicated insensitivity to nuclear structure, but also suggested a contributing role from the elementary nucleon-nucleon reaction mechanism (the $\vec{p}p\rightarrow d\pi^{+}$ analyzing power[6]). To date all theoretical attempts, based mainly on the SNM, have been singularly unsuccessful at describing the features of the analyzing power experimental results.[4]

In this paper the energy dependence of the analyzing power for the $^9Be(\vec{p},\pi^+)^{10}Be$ reaction to a number of states in ^{10}Be was investigated at the energy region of 225 to 250 MeV, although some measurements were also taken at 200 MeV as a test of consistency with previous data.[5] Measurements, in the same energy range, for the $^{12}C(\vec{p},\pi^+)^{13}C$ reaction are reported elsewhere.[7] The detection system consisted of a 65 cm Browne-Buechner magnetic spectrograph with helically wound multiwire proportional chambers for momentum analysis and a three-counter coincidence for definition of the fast trigger. Pions were identified on the basis of energy loss, time of flight, and track reconstruction. 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. A typical excitation spectrum at 250 MeV is shown in Fig. 1.

The polarization of the proton beam, $\sim 70\%$, was measured using elastic *p-p* scattering in a 4-arm 8-counter polarimeter that detected scattered and recoil protons both to the left and right of the beam direction. The beam intensity (5–20 nA) was also measured by the polarimeter giving a measure of the total integrated proton flux to an accuracy of $\sim 10\%$.

The analyzing power $A_y(\theta)$ was calculated using the equation

$$A_y(\theta)=\frac{Y_N(\uparrow)-Y_N(\downarrow)}{P(\uparrow)Y_N(\downarrow)+P(\downarrow)Y_N(\uparrow)} ,$$

where P and Y_N are the beam polarization and normalized yield, respectively. The arrows indicate the spin direction according to the Madison convention.[8]

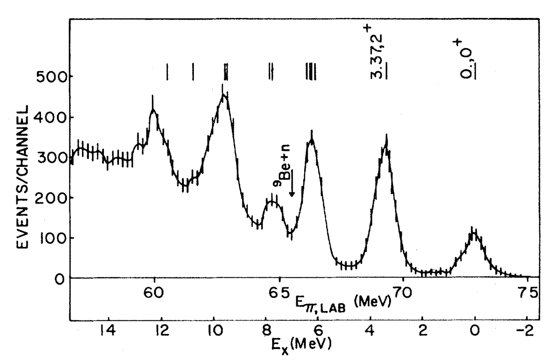

FIG. 1. Energy spectrum for pions produced by 250 MeV protons at $\theta_{\pi,\mathrm{lab}}=46.5°$. Both pion kinetic energy and nuclear excitation energy are shown. The markers indicate excitation levels reported in the literature (Ref. 10). The solid line through the data points is intended only as a guide to the eye.

As can be seen in Fig. 1, only transitions to the $^{10}Be_{g.s.}(0^+)$ and the $^{10}Be^*_{3.37}(2^+)$ state are clearly resolved. The group of states around 6.0 MeV are also strongly excited, as are also separate pairs of states near 7.5 and 9.5 MeV.

The analyzing power for the transitions to the ground and 3.37 MeV excited states are shown in Figs. 2 and 3, respectively. As can be seen in Fig. 2(a), our present results (solid circles) indicate larger negative analyzing power in the 60°–80° region at 200 MeV for the $^{10}Be_{g.s.}$ transition than the results from Ref. 5 (open circles). We believe the new data are more reliable because the improved resolution and reduced sensitivity to pion multiple scattering effects characterizing the present system leads to a better signal-to-noise ratio than was the case for the earlier measurements. For the higher peak-to-background ratio (see Fig. 1) characterizing transitions to the $^{10}Be^*_{3.37}$ state, the older measurements were less subject to such backgrounds, with the result that the agreement between the results reported here and those of Ref. 5 is excellent, as can be seen in Fig. 3(a).

When compared to the dramatic energy dependence observed in the $^{12}C(\vec{p},\pi^+)^{13}C_{g.s.}$ reaction[7] (open triangles of Fig. 2) the energy dependence characterizing the $^9Be(\vec{p},\pi^+)^{10}Be_{g.s.}$ reaction is more subtle. In the case of the ^{12}C reaction the change in $A_y(\theta)$ takes place throughout the angular range 46°–135°, while in the ^9Be case there is little energy dependence of $A_y(\theta)$ at forward angles, whereas a large dependence occurs for angles greater than 90°. Furthermore, the analyzing power for the transitions leading to $^{13}C_{g.s.}$ and $^{10}Be_{g.s.}$ is quite similar for $\theta_\pi \gtrsim 110°$. This common behavior of $A_y(\theta)$ in the back angles suggests that polarization effects are not dependent on specific nuclear structure details in this angular region, but depend instead on more general aspects of the reaction process. However, when restricting attention to angles $\lesssim 90°$, the difference in the energy dependence for the two nuclei is dramatic. In this angular range the analyzing power $A_y(\theta)$ for the $^{10}Be_{g.s.}$ transition remains essentially unchanged, while for $^{13}C_{g.s.}$ the analyzing power has reversed sign.

The overall effects observed above are also evident in Fig. 3 for the $A_y(\theta)$ of the transition leading to the $^{10}Be^*_{3.37}$ state; here, however, the very forward angle $A_y(\theta)$ shows a gradual increase to positive analyzing powers with increasing incident energy.

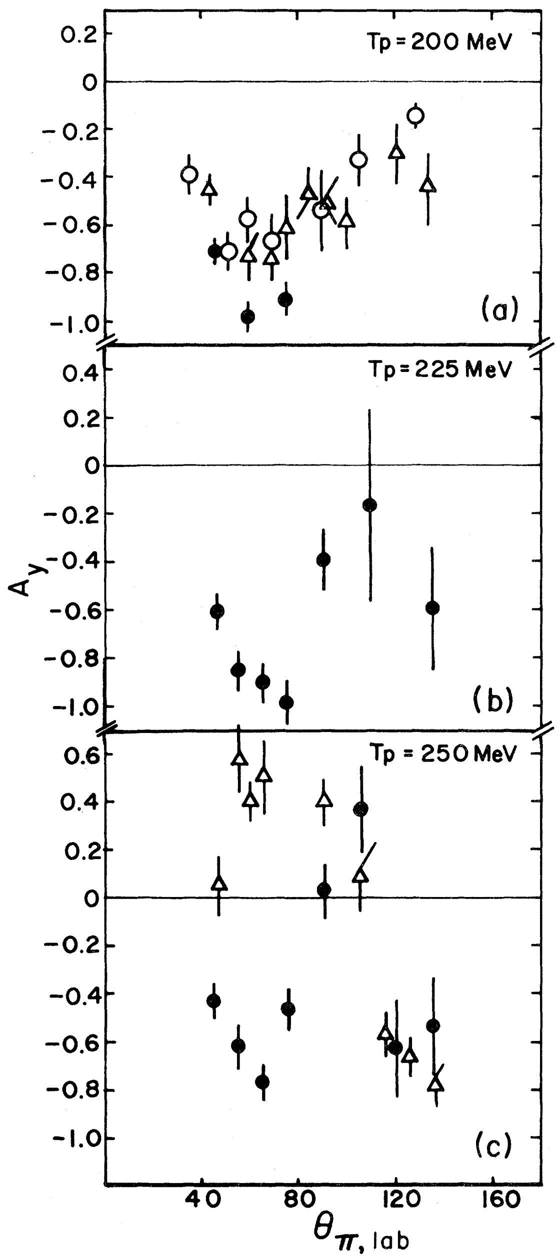

FIG. 2. The analyzing power for the $^{10}Be_{g.s.}$ transition for (a) 200 MeV, (b) 225 MeV, and (c) 250 MeV incident proton energy. The open circles in (a) are from Ref. 5 while the open triangles are for the transition leading to $^{13}C_{g.s.}$ in the reaction $^{12}C(\vec{p},\pi^+)^{13}C_{g.s.}$ from Ref. 7. Only statistical errors are shown.

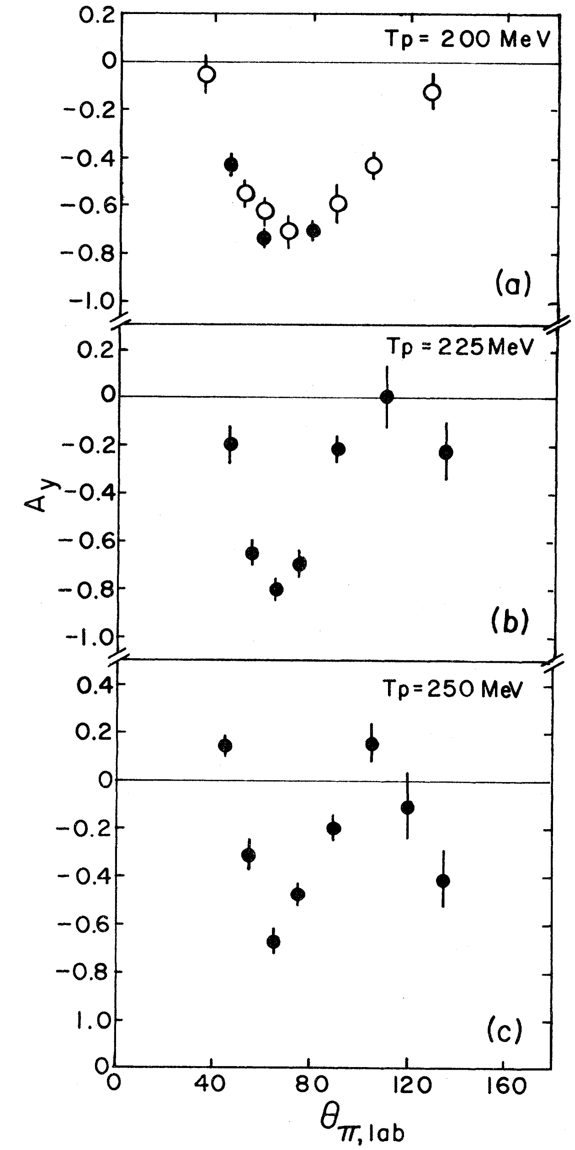

FIG. 3. The analyzing power for the transition leading to $^{10}Be_{3.37}$ for (a) 200 MeV, (b) 225 MeV, and (c) 250 MeV. The open circles in (a) are from Ref. 5. Only statistical errors are shown.

At 250 MeV, even though our spectrometer is restricted to angles greater than 45°, the two transitions in ^{10}Be do not exhibit the similarity in analyzing power at small angles reported at 200 MeV.[5]

Unfortunately the $^{9}Be(\vec{p},\pi^+)^{10}Be$ reaction has not been investigated at incident polarized proton energies below 200 MeV or above 250 MeV. Since the $^{12}C(\vec{p},\pi^+)^{13}C$ reaction showed such a dramatic change in $A_y(\theta)$ between 200 and 225 MeV, it is conceivable that for ^{9}Be it occurs at energies higher than the 250 MeV investigated here. For $^{12}C(\vec{p},\pi^+)^{13}C$ the analyzing power near threshold[9] was observed to be essentially identical to that measured at 200 MeV.[5,7] Whether this implied independence on proton energy near threshold occurs for $^9Be(\vec{p},\pi^+)^{10}Be$ as well is not yet known.

Clearly the $(\vec{p},\pi^+)$ reaction must be explored in greater detail before any realistic conclusions can be drawn. Test case nuclei such as ^{12}C, ^{13}C, ^9Be, ^{10}B, and ^{16}O (as well as others) must be explored in the widest energy range possible in order to seek out systematic effects in both analyzing power as well as differential cross sections, since at the present time the amount of such experimental data is very limited.

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