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Negative-Pion Production from the Bombardment of ^{9}Be with 200-MeV Polarized Protons

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Angular distributions of the analyzing power $A(\theta)$ and the differential cross section $d\sigma(\theta)/d\Omega$ for the reaction ^{9}Be($p_{\rm pol}$, π^-)^{10}C(g.s.) have been measured with 200-MeV polarized protons at laboratory angles between 25° and 150°. The measured $A(\theta)$, which is negative for $\theta_\pi^{\rm c.m.} \lesssim 70°$ and positive thereafter, is quite different from those of ($p_{\rm pol}$, π^+) reactions, for which $A(\theta)$ is typically negative at all angles. The present $d\sigma(\theta)/d\Omega$ is backward peaked, unlike all previously measured (p, π^-) distributions.

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Proton-induced pion production that leaves the nucleus in a discrete final state is receiving considerable attention, since an understanding of this production process, which involves large momentum transfer to the residual nucleus (typically $\gtrsim 450$ MeV/c), may increase our knowledge of meson-nucleus dynamics and provide new information on nuclear structure. Both the experimental and theoretical aspects of pion production have been reviewed recently by Hoistad[1] and by Measday and Miller.[2]

Of the three pion-production channels, (p, π^-) is interesting since it is a double-charge-exchange reaction involving the transfer of only one nucleon. Consequently this reaction, unlike positive- and neutral-pion production, is forbidden by single-nucleon mechanisms. This feature may prove to be useful for examining the role played by more complex reaction mechanisms of pion production and in probing Δ^{++} isobar components of nuclear wave functions.[3] Presently, little is known about the (p, π^-) reaction. The few measured[4-7] differential-cross-section angular distributions are isotropic, or nearly so, and the total cross sections are all $\lesssim 30$ nb. This is in contrast to the (p, π^+) reaction, which typically has differential cross sections with strong angular dependence and total cross sections as large as 2 μb. Virtually nothing is known experimentally about the energy dependence of the (p, π^-) reaction[6,8] and analyzing-power measurements have not been reported previously.

None of the theoretical calculations[3,9-13] of differential cross sections for negative-pion production can be regarded as satisfactory. Calculations using Δ^{++} transfer[3] or direct nucleon transfer (with charge exchange in the initial- or final-state interactions)[3,9] fail to reproduce the experimental distributions. Results from the application of the two-nucleon model[10-12] (TNM) have had only qualitative successes. A more recent attempt to describe the (p, π) reaction assumes that the dominant mechanism is direct knockout from the nuclear pionic field.[13] An interesting result

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of this model is the prediction that (p_{pol},π^-) analyzing powers can be positive and quite large in magnitude. If these predictions are accurate, such (p_{pol},π^-) analyzing powers would be opposite in sign to the measured analyzing powers for (p_{pol},π^+)[14,15] and (p_{pol},π^0).[16]

In this Letter we report the results of a measurement of the analyzing power for the reaction ^{9}Be$(p_{pol},\pi^-)^{10}$C(g.s.). This measurement, the first of a (p_{pol},π^-) analyzing power, was conducted at the Indiana University Cyclotron Facility with use of a beam of 200.3-MeV polarized protons on a 145-mg/cm^2 target of ^{9}Be. A single detection system for the pions was employed; attempts were made to reduce systematic errors resulting from this "one-arm" geometry by automatically reversing the beam polarization every 60 sec. The multiparameter events for each proton spin direction were accumulated in separate computer-generated arrays and written on magnetic tape for later analysis. The beam polarization (typically 70%) was measured periodically by inserting a ^{4}He gas cell into the beam between the injector and main-stage cyclotrons and comparing the observed asymmetry for $p+{}^4$He elastic scattering with the well-established analyzing powers for this reaction. (Analyzing-power measurements[17] of elastic scattering of protons by ^{12}C after acceleration of the beam to high energies indicate no significant change in the beam polarization in the main-stage cyclotron.) During actual data taking, the relative beam polarization was monitored at the target by detection of elastically scattered protons at ~ 20° in the laboratory.

The negative pions were detected with the quadrupole-dipole-dipole-multipole (QDDM) magnetic spectrograph and a focal plane array consisting of a position-sensitive helical wire chamber and three scintillators (see Bent *et al.*[18] for details). The scintillator thicknesses were selected so that the pions did not stop in the detector stack. Three energy-loss cuts, two position cuts, and two time-of-flight cuts typically reduced the background to less than 5% of the pion event rate. Corrections for in-flight pion decay and muons misidentified as pions were applied. The ^{10}C ground state, which, because of the small momentum bite of the QDDM spectrograph, nearly filled the focal plane, was still easily resolved from the first excited state at 3.35 MeV. The gain stability of the photomultiplier tubes and the system dead time were monitored with pulses generated by light-emitting diodes triggered by the monitor detector.

The results of the analyzing-power measurement, shown in Fig. 1, have been plotted as a function of the center-of-mass pion angle $\theta_\pi^{\text{c.m.}}$. The analyzing power is given by

$$A(\theta)=\frac{d\sigma(\uparrow)/d\Omega-d\sigma(\downarrow)/d\Omega}{p(\downarrow)d\sigma(\uparrow)/d\Omega+p(\uparrow)d\sigma(\downarrow)/d\Omega},$$

where p is the measured beam polarization, and the arrows indicate proton spin orientation. The sign convention for $A(\theta)$ follows the Madison convention.[19] The error bars in the analyzing-power data are based on statistical uncertainties; beam-polarization uncertainties were less than 3%. The solid line in Fig. 1 is the result of a least-squares fit to the (p,π^-) data of the form $A(\theta)=(d\sigma/d\Omega)^{-1}\times\sin\theta[b_0+b_1P_1(\theta)]$, where $d\sigma(\theta)/d\Omega=a_0+a_1P_1(\theta)+a_2P_2(\theta)$ and the $P_n(\theta)$ are Legendre polynomials. Adding the next term to each series did not reduce χ^2, and the resultant a_3 and b_2 coefficients were not significantly different from zero. Thus, there is no evidence for other than S and P waves in the outgoing pion angular distributions. For comparison, the analyzing powers of the reaction ^{9}Be$(p_{pol},\pi^+)^{10}$Be(g.s.), measured[14] at 200-MeV bombarding energy with a comparable center-of-mass pion energy ($T_\pi^{\text{c.m.}}\approx 40$ MeV), are shown in Fig. 1 also. Since ^{10}Be is the isobaric analog of ^{10}C, nuclear structure differences should be minimized in a comparison of the two reactions.

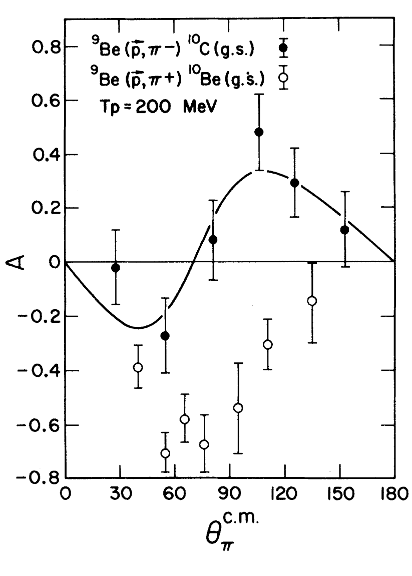

FIG. 1. The results of the present measurement of the analyzing power A for the reaction ^{9}Be$(p_{pol},\pi^-)^{10}$C(g.s.) at a bombarding energy of 200 MeV. The analyzing-power results for the reaction ^{9}Be$(p_{pol},\pi^+)^{10}$Be(g.s.), also measured at 200 MeV, are taken from Ref. 14. The solid line is the result of a least-squares fit to the data as described in the text.

The spin-averaged differential cross sections of the present ^{9}Be$(p,\pi^-)^{10}$C(g.s.) measurement are plotted in Fig. 2 as a function of momentum transfer q in units of MeV/c. The error bars are statistical only and the error in the absolute cross section is estimated to be ± 15%. Also included in this figure are the results[4] of the measurement of the same reaction at 185-MeV proton bombarding energy. For contrast, the dotted line in Fig. 2 is the result of a least-squares fit to the ^{9}Be$(p,\pi^+)^{10}$Be(g.s.) differential-cross-section data of Ref. 4 at 185-MeV bombarding energy. The 185-MeV (p,π^-) data cover an angular range of $39° \leq \theta_\pi^{\text{c.m.}} \leq 135°$ compared to $28° \leq \theta_\pi^{\text{c.m.}} \leq 154°$ for the present measurement.

As displayed in Fig. 1, the angular distribution of the analyzing power $A(\theta)$ for the reaction ^{9}Be$(p_{\text{pol}},\pi^-)^{10}$C(g.s.) is substantially different from that for the reaction ^{9}Be$(p_{\text{pol}},\pi^+)^{10}$Be(g.s.). For the (p_{pol},π^-) reaction, $A(\theta)$ is negative for $\theta_\pi^{\text{c.m.}} \lesssim 70°$ and positive thereafter, with a maximum value of 0.48 ± 0.14 at $\theta_\pi^{\text{c.m.}} = 106°$, whereas for the (p_{pol},π^+) reaction, $A(\theta)$ is negative over the entire angular range with a maximum absolute value as large as ~ 0.7. A negative $A(\theta)$ is a feature of nearly all (p_{pol},π^+) analyzing-power measurements.[14,15] There is also a large difference between the distributions of the differential cross sections (see Fig. 2). The (p,π^+) distribution is forward peaked, while that for (p,π^-) is backward peaked with a maximum value about an order of magnitude smaller than that for (p,π^+). Large differences in (p,π^-) cross sections have been observed also for the ^{12,13}C$(p,\pi^\pm)$ reactions at 185- and 200-MeV bombarding energies.[5,6] In contrast to these near-threshold studies, the measurement[20] of the ^{9}Be$(p,\pi^\pm)$ reactions at 800-MeV bombarding energy indicates that the shapes of the (p,π^+) and (p,π^-) differential-cross-section angular distributions are similar at forward angles, and that the ratio of the π^+-to-π^- production is larger than the ratio near threshold.

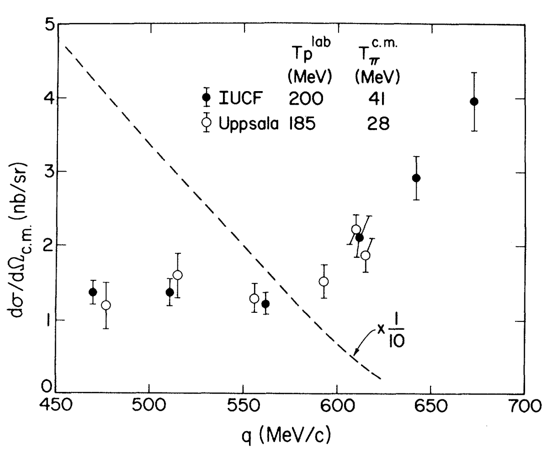

FIG. 2. The spin-averaged differential cross sections of the present ^{9}Be$(p,\pi^-)^{10}$C(g.s.) measurement plotted as a function of momentum transfer. The 185-MeV results are taken from Ref. 4. For comparison, the dotted line is a least-squares fit of Legendre polynomials to the ^{9}Be$(p,\pi^+)^{10}$Be(g.s.) differential cross sections at 185 MeV bombarding energy of Ref. 4.

The backward peaking in the present ^{9}Be$(p,\pi^-)^{10}$C(g.s.) differential-cross-section distribution is a feature which has not been observed in previous (p,π^-) distributions. As shown in Fig. 2, the earlier measurement[4] of the reaction ^{9}Be$(p,\pi^-)^{10}$C(g.s.) at a bombarding energy of 185 MeV did not cover a sufficiently large range of angle or momentum transfer to identify this feature. The other (p,π^-) angular distributions[5-7] measured near threshold ($T_\pi^{\text{c.m.}} \leq 50$ MeV) are isotropic within the experimental error, or in the case of ^{13}C$(p,\pi^-)^{14}$O exhibit a slightly peaked distribution with a maximum near $\theta_\pi^{\text{c.m.}} = 90°$. Thus, the present angular distribution measurement may signify a stronger (p,π^-) state dependence near threshold than indicated previously.

The excellent agreement between the present 200-MeV differential cross sections and those measured[4] at 185 MeV at overlapping momentum transfer indicate that the shape and, hence, the backward peaking in the ^{9}Be$(p,\pi^-)^{10}$C(g.s.) distribution is most likely determined by the momentum transfer. The possibility of some energy dependence in the cross section cannot be ruled out, however, since systematic differences in (p,π^+) absolute cross sections measured at the Indiana University Cyclotron Facility and at the University of Uppsala have been observed.[2] The near-threshold energy dependence of the (p,π^-) reaction will be investigated in future experiments. Comparison at similar q of the backward-peaked differential-cross-section distribution obtained at 200 MeV with the forward-peaked distribution at 800 MeV shows that there is substantial variation of shape with large energy differences.

Several theoretical models[3,9-13] have been used to calculate (p,π^-) angular distributions. However, calculations of the (p_{pol},π^-) analyzing power have been made only with the model proposed recently by Gibbs,[13] in which it is assumed that the production process is dominated by direct knockout from the nuclear pionic field. Preliminary calculations[13] with this model for the reaction ^{9}Be(p_{pol}, π^-)^{10}C(g.s.) at 200-MeV bombarding energy yield analyzing powers which are positive over the entire angular range and have maximum values ranging from + 0.4 to 0.6. Thus, there is qualitative agreement between experiment and theory at back angles, but disagreement at forward angles, where $A(\theta)$ is observed to be small and negative. Calculations of the differential cross sections for the reaction ^{9}Be(p, π^-)^{10}C(g.s.) have been made by Dillig and Huber[10] and by Reitan[11] at 185 MeV using the TNM, as well as by Gibbs.[13] None, however, obtained a backward-peaked distribution. The preliminary calculations by Gibbs give somewhat forward-peaked distributions, while the TNM distributions are nearly isotropic with a shallow minimum near $\theta_\pi^{c.m.} = 60°$. Absolute values for the differential cross sections are given only in the calculation by Dillig and Huber.[10] Their values (~ 1 nb/sr) are on the same order as the experimental data.

The results of this initial measurement show that the analyzing power of the reaction ^{9}Be(p_{pol}, π^-)^{10}C(g.s.) has a large positive component in contrast with that of (p_{pol}, π^+), and a differential cross section which increases with increasing momentum transfer. In future experiments it will be important to establish whether these features persist for (p, π^-) transitions to other final states and at other energies. The present experimental results clearly indicate the need for a more comprehensive theoretical interpretation of the (p, π^-) reaction than is presently available.

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