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Production of Positive Pions from the Bombardment of ^{9}Be and ^{12}C with 200-MeV Polarized Protons

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Differential cross sections and analyzing power for reactions ^{12}C(p,π^+) and ^{9}Be(p,π^+) leading to discrete final states in the residual nuclei have been measured in the angular range from 35° to 135° using 200-MeV polarized protons. The shape of the angular distribution of analyzing powers is essentially independent of the residual nuclear state, indicating a strong dependence upon reaction mechanism rather than nuclear structure.

The (p,π) reaction has attracted considerable interest since the pioneering studies of Dahlgren, Höistad, and Grafström,[1] in which individual nuclear states were resolved. The possibility of extracting interesting nuclear structure information has been the primary motivation for studying such reactions involving large momentum transfers. To make possible the extraction of such nuclear structure information, several models[2-8] for the reaction mechanism have recently been discussed.

With a single exception[9] all previous work in this area has been done with unpolarized proton beams. The (p,π) program at TRIUMF has employed a polarized beam[10] to permit measurements of the analyzing power of the pion production reaction as a function of production angle, as well as the differential cross sections which are normally used to test the reaction-mechanism models. Measurements of pion production associated with the bombardment of ^{12}C and ^{9}Be by 200-MeV protons are presented in this Letter.

Pions having energies up to 100 MeV were detected with a broad-range, 0.5-m-radius Browne-Buechner magnetic spectrograph. The detection system consisted of a 24-element scintillation counter hodoscope on the focal plane. An aperture counter and three additional scintillation counters above the focal plane provided timing and dE/dX information essential for reduction of background.[11]

Both the beam polarization and intensity were monitored during the runs using the (p,p) elastic scattering reaction occurring at a thin CH_2 target located downstream of the pion production target. A monitor count corresponded to the coincident detection of a proton scattered at 26° to the left (right) with respect to the beam direc-

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tion and a recoil proton detected at 60° to the right (left). The analyzing power of this monitor varied from 0.27 ± 0.01 to 0.36 ± 0.02 in the proton energy range of 200 to 500 MeV. Typical beam polarization was 65%. The intensity calibration was approximately one monitor count for each $(4.2 \pm 0.6) \times 10^7$ protons in the beam. A series of carbon activation measurements for the whole proton energy range gave calibrations with a mean deviation of 1.7% from intensity calculations based on (p,p) elastic scattering cross sections. When the spectrograph was at large angles, the limit in the proton beam intensity was 5 nA because of high random rates in the polarimeter counters. At most forward angles, high rates in the aperture counter limited the useful current to 1 nA.

Particle time of flight with respect to the cyclotron radio frequency, as well as individual pulse-height data, was recorded on magnetic tape for each event. Some system diagnostics were available on line. The principal analysis was subsequently carried out using the IBM 370 computer at the University of British Columbia. Data were recorded with 99-mg/cm^2 ^{9}Be and 147-mg/cm^2 ^{12}C targets, and also with no target to determine the background due to the 10 mg/cm^2 of air in the target vicinity.

The momentum distribution of pions from the reaction $^{12}C(p,\pi^+)^{13}C$ at a pion lab angle of 60° is shown in Fig. 1(a). Pions with the highest observed momenta are counted in the higher numbered hodoscope counters. As indicated in the figure the ^{13}C ground state has been clearly resolved. Pions leading to the first three unresolved excited states of ^{13}C are also separated from lower-energy pions associated with other reaction channels.

The differential cross section for a reaction leaving the residual nucleus in a particular ^{13}C state is given by

$$\frac{d\sigma}{d\Omega} = \frac{N}{N_{tgt} N_p \Delta\Omega \epsilon_\pi}.$$

The number of target atoms per unit area, N_{tgt}, includes the effect of the target angle with respect to the beam. N is the number of pions after random subtraction with all timing and pulse-height cuts applied. Random event rates were typically about 1% of real pion events. The integrated beam current in protons, N_p, has been determined from the polarimeter monitor. The solid-angle acceptance of the spectrograph, $\Delta\Omega$, is 4.6 ± 0.5 msr. Pion decays within the detection

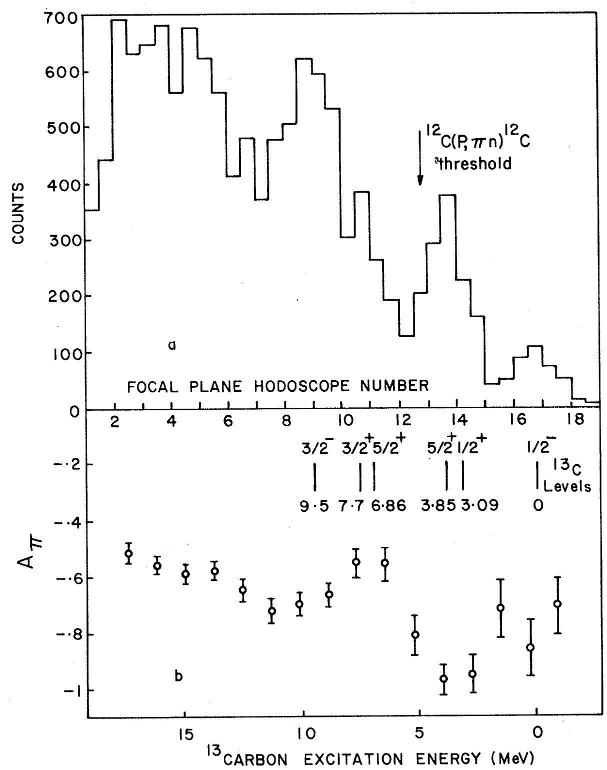

FIG. 1. Upper histogram: A $^{12}C(p,\pi^+)^{13}C$ spectrum for $\theta_{lab} = 60°$, and incident protons with spin down. The abscissa is the pion position on the focal plane as measured by the hodoscope counters. The second curve is the A_π at the same angle. The abscissa scale is the same same as for the first curve but shown in terms of the excitation energy of ^{13}C.

system and decay muons falsely detected as pions are accounted for in the efficiency factor, ϵ_π.

The spin-averaged differential cross sections for the reactions $^{12}C(p,\pi^+)^{13}C$(g.s.) and $^{12}C(p,\pi^+)^{13}C^*$ are shown in Figs. 2(a) and 3(a) as a function of pion lab angle. The error bars shown are a combination of statistical uncertainties and uncertainties in the peak width. Absolute uncertainties previously indicated combine to approximately ±30%. Previous data from Dahlgren *et al.*[12] have also been plotted.

The analyzing power is given by

$$A_\pi = \frac{d\sigma(\uparrow)/d\Omega - d\sigma(\downarrow)/d\Omega}{P(\downarrow)d\sigma(\uparrow)/d\Omega + P(\uparrow)d\sigma(\downarrow)/d\Omega},$$

where the arrows indicate proton spin orientation and P is the measured beam polarization. The sign convention for A_π follows the Madison convention.[13] That is, $d\sigma(\uparrow)/d\Omega$ is the differential cross section measured when the proton spin is

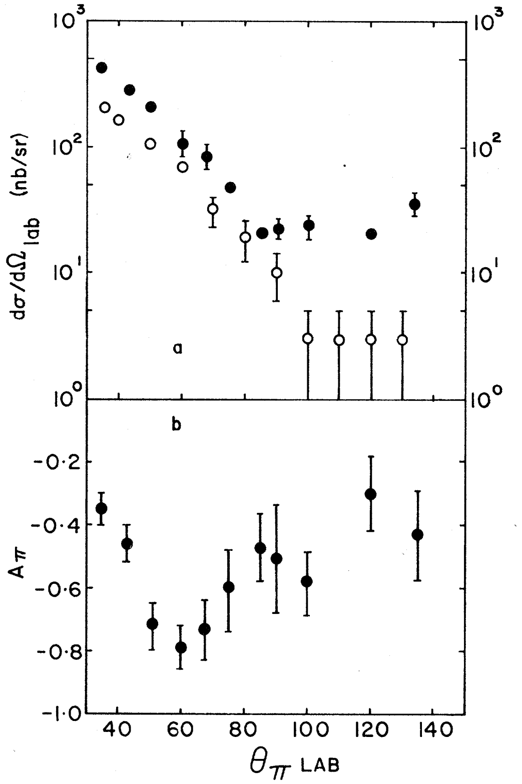

FIG. 2. Angular distributions of cross section and A_π for the reaction $^{12}C(p,\pi^+)^{13}C$(g.s.). The solid circles are the present work, and open circles are data from Ref. 12.

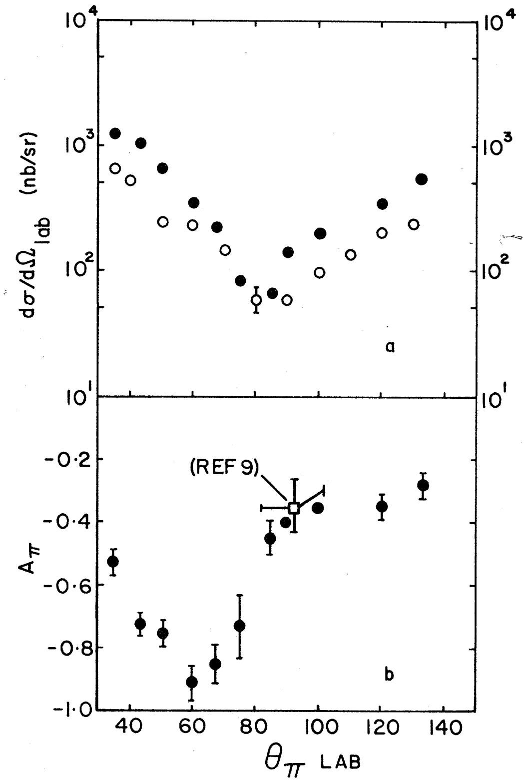

FIG. 3. Angular distributions of cross section and A_π for the reaction $^{12}C(p,\pi^+)^{13}C^*$(3.09, 3.68, 3.85 MeV). The solid circles represent the present work, and the open circles are the sum of the corresponding resolved peaks from Ref. 12.

in the direction $\vec{k}_p \times \vec{k}_\pi$. The analyzing power for the reaction $^{12}C(p,\pi^+)^{13}C^*$ as a function of the excitation of the ^{13}C nucleus is shown in Fig. 1(b). Figures 2(b), 3(b), and 4 illustrate the angular dependence of the analyzing power for a number of different final states of ^{13}C and ^{10}Be. Error bars in all A_π data presented are based on statistical uncertainties. A further systematic uncertainty of $\pm 5\%$ follows from the uncertainties in the analyzing power of the (p,p) elastic scattering reaction at 200 MeV, used to measure the beam polarization.

The shapes of the angular distributions of the differential cross sections do not differ significantly from those observed by Dahlgren *et al.* As also observed at proton energy of 185 MeV,[14] the angular distributions have a relatively structureless slope for those cases where the neutron is captured into a p shell, as in the case of ^{13}C ground state. In the case of the first three ^{13}C excited states the neutron is captured to a $2s$ or $1d$ shell, and the angular distribution has a dramatic upswing at large angles.

The most striking feature of these results is the almost universal shape of the analyzing power which is always very large and negative near 60° lab angle. This characteristic is common to

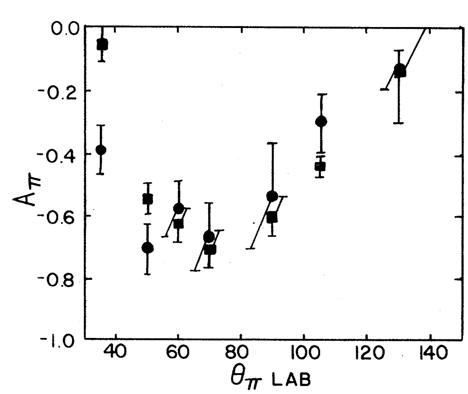

FIG. 4. Angular distributions of A_π for the reactions $^9Be(p,\pi^+)^{10}Be$(g.s.) (solid circles) and $^9Be(p,\pi^+)^{10}Be^*$ (3.37 MeV) (solid squares).

all reactions studied, those with the residual nuclei in their ground states, lowest excited states, and even at higher excitations in the region of breakup reactions. This is inconsistent with current theoretical predictions based on pion stripping models,[6,7] although most calculations for pion production to date do not include considerations of A_π.

The characteristics of the A_π suggest that its form is largely dictated by the reaction mechanism rather than by nuclear structure. The sign and simple angular structure of the observed analyzing power for these reactions is similar to the corresponding data for the reaction $p+p \to d+\pi^+$.[15] Thus, the analyzing power in the nuclear pion production reaction appears to reflect the basic N-N pion-production analyzing power in the sense expected from an impulse approximation[16] rather than being dominated by gross nuclear effects as expected from the single-nucleon models.

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Effect of Nuclear Deformation on Heavy-Ion Fusion

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The cross sections for the fusion of ^{16}O with the spherical and deformed isotopes of Sm measured at bombarding energies spanning the fusion barrier indicate the importance of nuclear deformation for the fusion process. Calculations based on the usual static treatment of deformation effects, however, show significant discrepancies with the experimental data.

The deformation of one or both of the partners in a heavy-ion reaction is expected to influence the probability that the partners will fuse to form a compound nucleus. The effect on the fusion cross section is also expected to differ according to whether the deformation is static or dynamically induced.[1,2] For a given bombarding energy, the cross section for fusion with a rigid, deformed nucleus should exceed that of a comparable spherical nucleus when averaged over all initial orientations.[1,3] Dynamic effects such as the excitation of vibrational states or the rotation of the deformed nucleus during the collision, however, are expected to reduce the fusion cross

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