Analyzing powers for the ^{3}He($\vec{p}$,π^+)^{4}He reaction in the region of the Δ_{1232} resonance

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Angular distributions of the analyzing powers have been measured for the ^{3}He($\vec{p}$,π^+)^{4}He reaction at proton bombarding energies of 300, 416, and 507 MeV. These results, together with existing measurements at 178, 198, and 800 MeV, provide a comprehensive set of data spanning the region of the Δ_{1232} resonance. The results are compared with a phenomenological model that incorporates the amplitudes for the $pp \rightarrow d\pi^+$ reaction and calculations from a microscopic (p,π^+) model.

Proton-induced nuclear pion production has been the subject of intensive study for the past 20 years, beginning with the pioneering work at the Uppsala University Cyclotron [1] and followed by systematic investigations of $A(p,\pi^+)A+1$ reactions using polarized beams. In particular, there exists a large body of data for exclusive nuclear pion production reactions with detailed measurements of the differential cross sections and the analyzing powers at energies near threshold from Indiana University Cyclotron Facility (IUCF) [2]. In the region of the Δ_{1232} resonance, less extensive data exist, largely from measurements at TRIUMF [3]. The theoretical effort has also been substantial. Several microscopic calculations [4] have been able to reproduce reasonably well data for specific reactions, but it has proven to be very difficult to develop a general model for $A(p,\pi^+)A+1$ reactions that describes a large body of data.

On a more qualitative level there is strong empirical evidence that the exclusive (p,π^+) reaction is mediated by a process, or processes, like the elementary $pp \rightarrow d\pi^+$ reaction [5]. Presently the objective is to elucidate the role of the elementary $NN \rightarrow NN\pi$ processes in this reaction despite the shortcomings of the microscopic calculations. Indeed, Korkmaz *et al.* recently interpreted pion production on ^{12,13}C nuclei at 200 MeV in terms of the $pp \rightarrow d\pi^+$ reaction results with considerable success [6]. As a complement to studies on light nuclei, an essential step in such an approach is to understand pion production in few-nucleon systems. To this end an experiment was performed to measure the analyzing powers and differential cross sections as a function of angle and incident proton energy for the ^{3}He($\vec{p}$,π^+)^{4}He reaction. There are analyzing power data near threshold at 178 and 198 MeV from IUCF [7] and at 800 MeV from LAMPF [8], but there remains a large gap between these energies in the region of the Δ_{1232} resonance. It was in this region that the present measurements were made.

The experiment was performed in the TRIUMF proton hall using the medium resolution spectrometer (MRS). Achromatic polarized proton beams of 300, 416, and 507 MeV, with typical momentum resolutions of $\Delta p/p \approx 0.2\%$, were extracted from the TRIUMF cyclotron. These beams were incident on a liquid-^{3}He target with intensities ranging from 5 to 40 nA, and with typical polarizations of 70%. The University of Manitoba–TRIUMF liquid-^{3}He target [9], comprised of a ^{3}He cell about 44 mm in diameter and 11 mm thick, was used in the experiment. The target was maintained at a stable temperature of 1.9 K, which corresponded to an areal density of about 85 mg/cm^2. Beam polarization was measured using an in-beam polarimeter. The statistical uncertainty in the analyzing powers due to the placement of software cuts and extraction of the peak area above background was typically ± 0.04. The systematic uncertainty is dominated by the uncertainty of the $pp \rightarrow pp$ analyzing powers (taken from SAID [10]), that are used to determine the beam polarization. This uncertainty was determined to be about 2%.

The results for the analyzing powers at the three energies of 300, 416, and 507 MeV are presented in the left-hand column of Fig. 1, together with the 198-MeV data of Ref. [7]. While the 198-MeV results show a pattern

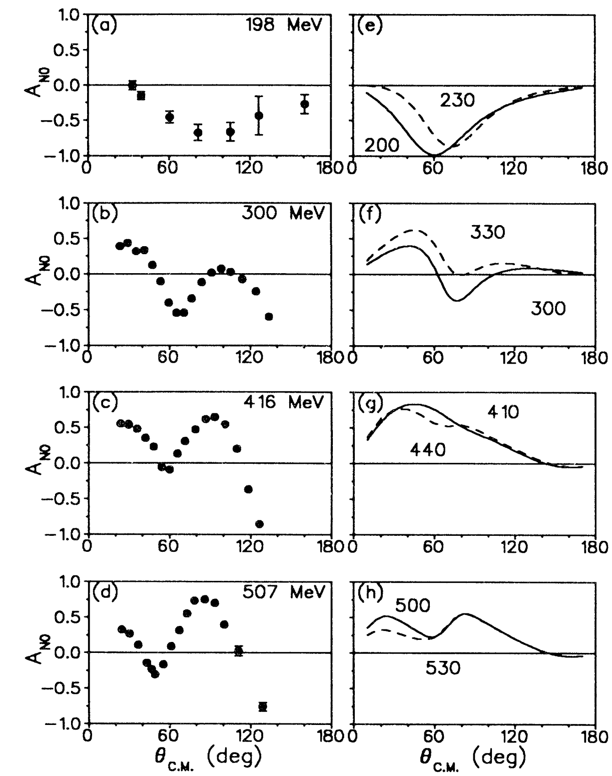

FIG. 1. Analyzing powers for the ^{3}He$(\vec{p},\pi^+)^4$He reaction. (a) Experimental data from Kehayias *et al.*, see Ref. [7]. (b)–(d) Experimental data from this work. (e)–(h) Predictions of a phenomenological $pp \to d\pi^+$ model. The solid lines are the lower energy and the dashed lines are the higher energy.

which is typical of the $pp \to d\pi^+$ analyzing power at low energies, we observe a dramatic change in character as the energy is increased to 300 MeV. There are large and rapid oscillations in the analyzing powers and this oscillating character occurs also in the 416- and 507-MeV data. The 800-MeV results of Ref. [8] (not shown) likewise represent a continuation of this pattern. We further note that the first minima in A_{N0} correspond to nearly constant values of the momentum transfer $q_{\mathrm{c.m.}}$. This quantity varies from about 2.7 fm^{-1} at 300 MeV to 3.0 fm^{-1} at the three higher energies.

Results from numerous recent measurements provide convincing evidence that the $pp \to d\pi^+$ process is the underlying mechanism in exclusive as well as inclusive nuclear pion production. Comparisons between the analyzing powers for discrete as well as continuum final states of light nuclei and those of the $pp \to d\pi^+$ reaction, kinematically transformed to the nuclear frame, exhibit strong similarities [6,11]. For inclusive reactions in the quasifree region at 400 and 450 MeV it has been shown that the results observed are consistent with a model based on the elementary $pp \to d\pi^+$ and $pp \to pn\pi^+$ pion production processes [12]. All this would suggest that a phenomenological model based on the elementary processes might provide useful insights into nuclear pion production. Indeed, there have been several calculations of this type where details of the $pp \to d\pi^+$ reaction were used as input to model calculations [13]. These calculations, however, used only the cross-section information and were therefore unable to predict spin observables.

We have developed a phenomenological model of the $A(p,\pi^+)A+1$ reaction that incorporates the $pp \to d\pi^+$ reaction amplitudes [14] and assumes this $NN \to NN\pi$ reaction as the primary pion production mechanism. The formulation follows the general outline presented by Ingram *et al.* [15] with several important extensions. The model allows for the effects of absorption of the incident proton and outgoing pion by attenuation factors in the plane waves. Amplitudes for the $pp \to d\pi^+$ reaction were parametrized as a continuous function of the incident proton laboratory energy from threshold to 800 MeV. Both the momentum distribution of the struck target proton and the recaptured deuteron are contained in the formulation. Simple shell-model configurations, $(1s)^3$ and $(1s)^4$, were assumed for the target and residual nuclei, respectively.

In the model, the struck target proton has a laboratory momentum p_2 and is assigned an energy $E_2 = M_A - (M_R + p_2^2/2M_R)$, where M_A is the target mass and M_R is the mass of the $A-1$ recoil. This expression thus assumes an on-shell recoil nucleus. From the energies and momenta of the two protons, E_1, $\mathbf{p}_1$ and E_2, $\mathbf{p}_2$, all the requisite quantities in the pp c.m. frame are calculated, including the pion momentum at its kinematically mandated (laboratory) value. The deuteron and the struck proton are both off shell. In order to determine the effective energy at which the $pp \to d\pi^+$ amplitudes are evaluated, one dynamical parameter must be specified. This dynamical parameter was taken to be the pion momentum in the pp c.m. frame. Justification for this choice, rather than the choice of the total energy in the pp c.m. frame, for example, was based on the success of this procedure in interpreting the $pp \to pn\pi^+$ analyzing powers [16]. The direction of the pion momentum with respect to the direction of the total momentum of the pp system was used to define the scattering angle of the pion in the pp c.m. frame. A more complete description of this model will be published at a later date.

The results of the calculation are shown in the right-hand columns of Fig. 1 for several energies in the neighborhood of the energies of the experimental data. The rapid changes in A_{N0} between 198 and 300 MeV observed in the experimental data are qualitatively reproduced by the calculation. At the two higher energies there remains some measure of qualitative agreement at the forward angles, but the calculation fails to reproduce the minima observed. There appears to be both an energy shift and an angular shift (momentum transfer) in comparing the calculations with experimental data. A feature of the predictions of this model is that the magnitude of the analyzing power can be much greater than that of the $pp \to d\pi^+$ reaction. The restrictions imposed by angular-momentum coupling dictate that the amplitudes for the $A(p,\pi^+)A+1$ reaction combine with different weightings than in $pp \to d\pi^+$. Different final states should thus exhibit structure dependence of A_{N0}. The calculations of A_{N0} revealed only a weak dependence on the attenuation factors (mean free paths) of the proton and pion.

Differential cross sections, on the other hand, were quite sensitive to these parameters, as expected. (These will be presented in an upcoming publication.)

The model presented includes only the ($T_i=1$, $T_f=0$) $NN \rightarrow NN\pi$ isospin channel, corresponding to the isospin cross sections σ_{10d} and σ_{10} (Ref. [17]). The spin dependence for the unbound NN state was assumed to be the same as for the bound NN state. This is observed to be the case at low relative NN energies [16] (in the final state). At higher relative NN energies—of increasing importance at higher bombarding energies—these assumptions may not be valid. Furthermore, the effective pp collision energies can attain values where the ($T_i=1$, $T_f=1$) channel is far from negligible. Indeed, for proton bombarding energies of 200, 300, 410, and 500 MeV in ^{3}He(p,π^+) the effective pp collision energies are often—depending on $\mathbf{p}_2$—in the range of 300, 450, 600, and 750 MeV, respectively. At these latter energies the ratio σ_{11}/σ_{10d} is about 0.01, 0.15, 0.60, and 2.3, respectively [18]. Possible interference of amplitudes from the ($T_i=1$, $T_f=1$) transition with those of the ($T_i=1$, $T_f=0$) transition could become of increasing importance as the energy is raised. However, presently little information exists on these amplitudes and no further quantitative estimates can be made.

Recently, a microscopic (p,π^+) model calculation of A_{N0} for the ^{3}He$(\vec{p},\pi^+)^4$He reaction was performed by Bent *et al.* [19]. The model microscopically includes both the one-nucleon mechanism and the resonant p-wave rescattering part of the two-nucleon mechanism, which is assumed to proceed through formation of the intermediate Δ_{1232} resonance induced by π and ρ meson exchange between the projectile and one target nucleon. Higher-order processes are included through proton-nucleus and pion-nucleus optical-model distortions. This model describes reasonably well the ^{3}He$(\vec{p},\pi^+)^4$He data of Ref. [7] at $T_p=178$ MeV and $T_p=198$ MeV (Ref. [19]). The results of a calculation at 300 MeV are compared with the present data in Fig. 2. The large and rapid oscillations observed at 300 MeV, but absent at 198 MeV [Fig. 1(a)], are indeed reproduced by the calculation, but the agreement with the data is only qualitative. Specifically, we note that the calculation gives the incorrect sign for A_{N0} at forward angles, although it reproduces the general trend of the data at back angles.

There are numerous reasons why the $pp \rightarrow d\pi^+$ model could fail. Among others, these include neglect of distortions, inadequate treatment of off-shell effects and pion rescattering, and inclusion of only the ($T_i=1$, $T_f=0$) NN isospin channel, as discussed previously. One might well expect that the on-shell $pp \rightarrow d\pi^+$ amplitudes involving pion-deuteron partial waves $l_\pi=0,1,2$ will suffer modifications in the nuclear medium that increase rapidly with increasing value of l_π. The amplitudes themselves reveal some discrepancies in their description of the analyzing powers for the $pp \rightarrow d\pi^+$ reaction in that the minima at the lower energies in the vicinity of 90° are somewhat shallow, and the forward-angle values at 700 MeV are too small. All these factors may contribute significantly to the failure of this model, particularly at the higher energies and/or large angles where the momentum transfer is correspondingly greater. Despite the large degree of momentum sharing inherent in this model, many of the assumptions made become less valid as the momentum transfer exceeds 3 fm^{-1}. It is less clear where the limitations of the microscopic model might occur. Incorporating the experimentally determined amplitudes of the dominant $pp \rightarrow d\pi^+$ reaction as in the former model ensures that this model naturally includes the effects from resonant and nonresonant intermediate states. Whether the microscopic model adequately incorporates the relative magnitudes of these effects remains to be determined.

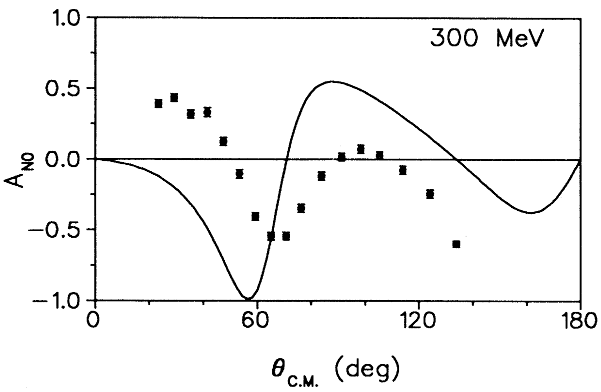

FIG. 2. Microscopic model calculation (Ref. [19]), compared with 300-MeV data from this work.

In a study of the ^{3}He$(\vec{p},\pi^+)^4$He reaction at 800 MeV, Höistad *et al.* [8] compared A_{N0} with that from $p+{}^3$He scattering, the $pp \rightarrow d\pi^+$ reaction, and πN scattering. Only for the latter process was there some qualitative agreement with ^{3}He$(\vec{p},\pi^+)^4$He analyzing powers when reasonable assumptions about momentum sharing were invoked. We note that, for $\vec{p}+{}^3$He elastic scattering, the first minima in A_{N0} occurs at a nearly constant $q_{\mathrm{c.m.}} \approx 2.8$ fm^{-1} (Ref. [20]).

We have presented analyzing power results for the ^{3}He$(\vec{p},\pi^+)^4$He reaction from 300 to 500 MeV. The results show large and rapid oscillations with characteristics of diffractionlike behavior, quite unlike typical results observed at 200 MeV. Predictions of two very different models have also been presented and discussed. Both models describe satisfactorily the analyzing powers at 200 MeV. At 300 MeV the microscopic model fails most seriously at forward angles where it predicts the wrong sign of A_{N0}. On the other hand, the $pp \rightarrow d\pi^+$ model describes reasonably well the forward-angle part of the A_{N0} distribution although it fails at the larger angles. The data presented in this work, together with those measured at 178, 198, and 800 MeV, provide a comprehensive data set spanning the region of the Δ_{1232} resonance. Such a complete data set provides a testing ground for theoretical and phenomenological models of proton-induced pion production in few-nucleon systems. It is hoped that this will stimulate renewed interest and effort in investigating this long-standing problem in pion physics.

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