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Angular distribution of the reaction $pd \rightarrow {}^3\mathrm{He}\pi^0$ at 800 MeV

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The angular distribution of the $pd \rightarrow {}^3\mathrm{He}\pi^0$ reaction at 800 MeV was measured and compared to a common (p,π) model. The data are consistent with other data in this energy region and are in qualitative agreement with predictions of the model. There are quantitive differences between data and theory.

[NUCLEAR REACTIONS ${}^2\mathrm{H}(p,{}^3\mathrm{He})\pi^0$, T_p= 800 MeV, measured $d\sigma/d\Omega$, compared with Ruderman model.]

I. INTRODUCTION

The pion production reactions $pd \rightarrow {}^3\mathrm{H}\pi^+$ and $pd \rightarrow {}^3\mathrm{He}\pi^0$ have been investigated at a number of energies over the past several years.[1-4] However, complete angular distributions for incident energies above 600 MeV are not available. Originally, comparison of these two reactions was proposed as a test of isospin conservation,[5] and the older data consist of a number of measurements at isolated angles and energies. More recently the reaction $pd \rightarrow {}^3\mathrm{H}\pi^+$ has been investigated as an example of a (p,π) reaction, particularly since earlier data showed an enhancement at back angles at 470 MeV incident proton energy.[3] The more recent data do not show this enhancement[4] and now seem to fit the general trend of data observed at neighboring energies. These data may be described by a rapid fall at forward angles, with an almost flat distribution at the backward angles.

Theoretically, a number of different models have been applied to these reactions.[6-9] The most common approach has been to use variants of the approximation first introduced by Ruderman.[6] The idea is to use the impulse approximation with the experimental $pp \rightarrow d\pi$ cross section as basic input to the calculation. Fearing[7] has most carefully developed this approximation and obtains an equation for the (p,π) reaction in the form

$$\frac{d\sigma}{d\Omega} = K \left| F(\Delta) \right|^2 \left.\frac{d\sigma}{d\Omega}\right)_{pp\rightarrow d\pi} .$$

In this expression K is a kinematic factor, $F(\Delta)$ is a nuclear form factor evaluated at some momentum transfer Δ, and $d\sigma/d\Omega)_{pp\rightarrow d\pi}$ is the elementary cross section for $pp \rightarrow d\pi$ evaluated at an average two body energy and angle. Fearing indicates this model should work best near the resonance region.

For the specific reaction, $pd \rightarrow {}^3\mathrm{H}\pi^+$, his results are in reasonable agreement with data at proton energies below 500 MeV, but begin to disagree with the shape of the data as the energy increases. The introduction of distortion in both the incident and exit channels effectively renormalizes the cross section but does not change the shape of the angular distribution. In absolute value, the cross section with distortion at 600 MeV is above the data at forward angles and below the data at backward angles. Fearing states that this difficulty may in part be related to the choice of the energy used in evaluation of the $pp \rightarrow d\pi$ elementary cross section.

In several papers Green and collaborators[8] have investigated the $pd \rightarrow {}^3\mathrm{H}\pi^+$ reaction and reached somewhat different conclusions. In particular it is suggested that the average energy at which to evaluate the elementary cross section in the impulse approximation is difficult if not impossible to determine and that distortion effects are angle dependent. In addition, contrary to what is observed, the inclusion of correlations in the triton wave function produces a minimum in the cross section that becomes more pronounced as the energy (momentum transfer) increases. This minimum is related to the minimum in the charge form factor[10] of the three body wave function which occurs at a momentum transfer of about 3.3 fm^{-1}. This minimum was present in the calculation of Locher and Weber,[9] but was not reproduced by Fearing. As was pointed out by several of these authors, inclusion of the D state of the deuteron wave function will tend to fill in such a minimum. Indeed, as shown by Fearing and reproduced here, the D state provides the major contribution to the cross section at backward angles. Although the data show no evidence of structure, a wave function that correctly describes the high momentum portion of the three body form factor is obviously important in order to increase the calculated cross section at backward angles.

Recently Auld[4] *et al.* measured the analyzing power for the reaction $pd \to {}^3\mathrm{H}\pi^+$ at several energies below 500 MeV. Although in the Fearing model the two body cross section does not factor out of the expression for the analyzing power as it does in the differential cross section, one would like to make a comparison to the elementary analyzing power. The expected result should be small and positive, while the observed result is large and negative.[4] It is not clear at this time if this is a fundamental problem in the theory.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The present experiment reports a measurement of the $pd \to {}^3\mathrm{He}\pi^0$ reaction at 800 MeV and a comparison to the $pd \to {}^3\mathrm{H}\pi^+$ reaction at the same energy. The experiment was performed by detecting the recoiling ${}^3\mathrm{He}$ from the reaction in a magnetic spectrometer constructed by placing multiwire proportional detectors before and after a standard "*C*" magnet in the external proton beam line of the Los Alamos Meson Facility. The spectrometer had an angular range between 5° and 37°. The 5° forward limit was imposed by the maximum allowable deflection of the main beam by the fringe field of the spectrometer magnet. A 3.8 cm thick steel beam pipe was used to shield the main beam from these fringe fields. Helium bags were placed in the spectrometer arm to reduce multiple scattering. The target was a liquid deuterium cylinder enclosed in a kapton flask as described previously.[11]

The spectrometer was able to discriminate ${}^3\mathrm{He}$ events from background because a ${}^3\mathrm{He}$ recoil from the $pd \to {}^3\mathrm{He}\pi^0$ reaction has the lowest velocity and consequently the largest time of flight of all the *pd* reaction products. Furthermore, due to the double charge, ${}^3\mathrm{He}$ had the lowest magnetic rigidity ($B\rho$) and gave the highest pulse height when compared to other reaction products having similar momentum. Kinematically, the He momenta were double valued for a given scattering angle in the lab frame. That is, at the same lab angle, ${}^3\mathrm{He}$ recoils had two different momenta, corresponding to two different center of mass scattering angles.

To calibrate this experiment, a time of flight telescope was placed to intercept the proton recoil from the *pp* elastic reaction when a scattered proton traversed the magnetic spectrometer. This enabled an absolute magnetic field calibration and gave an additional check of the beam normalization. The detection of the $pd \to {}^3\mathrm{H}\pi^+$ reaction also employed time of flight and spectrometer arms simultaneously. The fact that the two detector arms overdetermined a two-body reaction increases the confidence in identifying a $pd \to {}^3\mathrm{H}\pi^+$ event. Hence, setting the pulse height discriminator level to just accept all ${}^3\mathrm{H}$ events (which is a factor of two lower than the pulse height for ${}^3\mathrm{He}$) assured acceptance of all ${}^3\mathrm{He}$ events and discriminated against most of the higher cross section background reactions such as $pd \to pd$, $pd \to ppn$, and $pd \to d\pi n$.

The time of flight and momentum of a particle traversing the spectrometer arm was used to determine the particle mass. In a two dimensional histogram of particle mass versus scintillator pulse height, the ${}^3\mathrm{He}$ events were well separated from other events. Particle separation in terms of $B\rho$ alone was not satisfactory due to the large multiple scattering of the ${}^3\mathrm{He}$. The description of the detectors, beam monitors, data acquisition system, and experimental apparatus was essentially identical to that described in several previous papers.[11] The spectrometer acceptance was determined by a Monte Carlo method also previously described[11] but for this experiment we included a more careful treatment of multiple scattering and energy loss.

Experimental statistical error was 3% while the Monte Carlo statistical error was 2%. The systemic errors came from the uncertainty of beam normalization, which was ±6%, and the uncertainty in the number of scattering centers, which was ±3%. Other systemic errors are due to (1) nuclear interactions between the ${}^3\mathrm{He}$ and the material in the spectrometer arm (mainly C, He, O, and H); (2) the approximate calculation of the rms multiple scattering angle θ_{rms} (Ref. 12) used in the Monte Carlo solid angle computation; and (3) the unmeasured pileup rate.

Based on the extrapolation from the ${}^3\mathrm{He}$ elastic and reaction cross section data, the probability of a nuclear reaction occurring within the length of the spectrometer arm was calculated to be about 3%. However, due to their complexity, nuclear reactions were not included in the Monte Carlo solid angle calculation. It is estimated that a maximum of +2.5% correction should be made, if one assumes that nuclear reactions which result in the removal of the scattered flux occurred within the various windows or at the front scintillator. The exact energy dependence of the correction is not known.

Multiple scattering which was incorporated into the solid angle calculation was a major correction. Monte Carlo calculations indicate that a 33% increment in θ_{rms} resulted in a 17% decrement in solid angle for a ${}^3\mathrm{He}$ momentum of 800 MeV/*c*. There are no experimental data on ${}^3\mathrm{He}$ multiple scattering at the momenta of interest for this experiment, but it was assumed that the rms multiple scattering angle could be determined to ±5% uncertainty in the experimental cross section. Finally, pileup was not measured but was estimated using the known resolving time to be about 4%.

The differential cross section for the reaction $pd \rightarrow {}^3\mathrm{He}\pi^0$ at 800 MeV obtained from the analysis of the experiment is shown in Fig. 1. In these data, the positive side of the error bars include the uncertainties due to pileup (4%), nuclear interaction (2.5%), multiple scattering (5%), and the total statistical error. The negative side of the error bars include statistical errors only.

Two $pd \rightarrow {}^3\mathrm{He}\pi^0$ data points obtained from a completely independent experimental setup (including a different magnet) at a later date are displayed in Fig. 1 by open circles. The data points of the separate experiment, $\theta_\pi = 33.5°$, almost duplicate each other while those at $\theta_\pi = 110°$ differ by approximately 9%. However, this is still within the total experimental error. The gap in c.m. pion angles between 50° and 95° corresponds to the region near the turning point of the ${}^3\mathrm{He}$ momentum vs lab angle kinematic locus. At the turning point the Jacobian transformation between the lab to c.m. reference frames approaches infinity; therefore, this interval was purposely avoided during the experiment to avoid the singularity.

III. DISCUSSION AND CONCLUSIONS

The data can be checked for consistency with other data in this energy region. The $pd \rightarrow {}^3\mathrm{H}\pi^+$ data obtained in this experiment and the 809 MeV $pd \rightarrow {}^3\mathrm{H}\pi^+$ data of Aslanides *et al.*[2] are shown in Fig. 1. In addition, these data are consistent with extrapolation of the excitation energy plots of Ref. 1 at $\theta_\pi = 40°$ and 130°. The solid curve in Fig. 1 is a prediction of the reaction using the impulse approximation model proposed by Fearing. This calculation used a correlated cluster wave function which reproduces the ${}^3\mathrm{He}$ charge form factor and a Hulthén *S* state with a 7% McGee-Partovi[13] *D* state wave function for the deuteron. The parameters for these wave functions are given by previous authors.[7,9] Inclusion of the *D* state is important and the calculated result is sensitive to the chosen form. Distortion was not included because Fearing has shown that a distorted-wave impulse approximation (DWIA) calculation in his model simply renormalized the distribution and does not change its shape. In fact, his DWIA calculations required renormalization by a factor of 2 or 3 to match the measured value of the cross sections. Therefore, in this model, a plane-wave impulse approximation (PWIA) calculation contains essentially all the information that may be determined about the reaction mechanism. Approximations in the model, wave functions, and distortion mask any exact comparison of the calculation to the absolute value of the cross section. The two body cross section $pp \rightarrow d\pi$ was obtained from an interpolation of the complied data in Ref. 14. Unfortunately, the equivalent two body energy used to obtain the cross section varies between 1000 and 1180 MeV, which is above most of the fitted data. The calculation was normalized to the data at the 10° point.

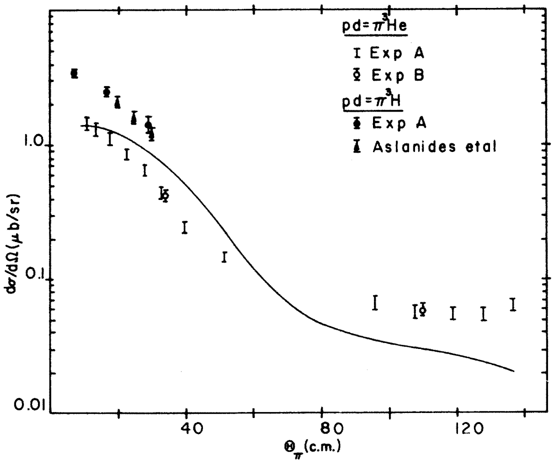

FIG. 1. The angular distribution of the reaction $pd \rightarrow {}^3\mathrm{He}\pi^0$ is shown along with the $pd \rightarrow {}^3\mathrm{H}\pi^+$ data and the data of Ref. 2 at 809 MeV. The curve is a PWIA calculation normalized at 10° as described in the text.

The calculation does not fall fast enough to match the slope of the data at the forward angles and is well below the data at the backward angles. This seems to be a general feature of this model since this is also observed at other energies. The ratio $\sigma({}^3\mathrm{H})/\sigma({}^3\mathrm{He})$ obtained from dividing the ${}^3\mathrm{H}$ data (interpolated to the ${}^3\mathrm{He}$ angle) by the ${}^3\mathrm{He}$ data is approximately 2 as predicted by isospin conservation. When the mass, charge, and wave function differences are taken into account, the ratio $d\sigma({}^3\mathrm{H})/d\sigma({}^3\mathrm{He})$ at 600 MeV was calculated to be 2.17.[5] Distortion in both the incident and exit channels for these reactions is nearly identical. The incident channel contains the same particles at the same energy. The exit channel contains the particles π^+ and ${}^3\mathrm{H}$ for one reaction and π^0 and ${}^3\mathrm{He}$ for the other. Assuming isospin conservation and the isobar model, the distorting potential given in the Glauber approximation[7] is almost identical for each reaction. Thus, distortion affects each calculation in essentially the same way, and the shapes of the experimental differential cross sections of the two reactions are basically the same with the same renormalization factor. In this case a PWIA calculation would give the correct cross

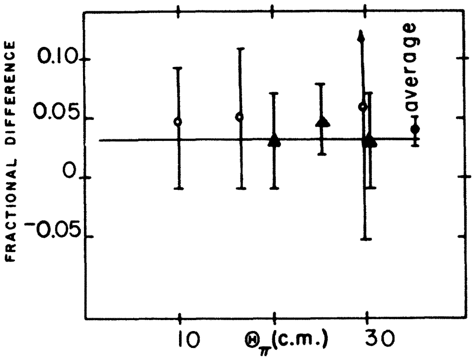

FIG. 2. The fractional difference $[d\sigma({}^3\mathrm{H})/d\Omega - 2d\sigma({}^3\mathrm{He})/d\Omega]/[d\sigma({}^3\mathrm{H})/d\Omega + 2d\sigma({}^3\mathrm{He})/d\Omega]$ is shown as a function of angle. The weighted average over angle of the data is also shown on the figure. The curve is a PWIA calculation as described in the text. The open circles represent the fractional difference determined from $pd \rightarrow {}^3\mathrm{H}\pi^+$ data taken in this experiment. The solid triangles are obtained from the $pd \rightarrow {}^3\mathrm{H}\pi^+$ data of Ref. 2.

section ratio.

The measured ratio of the cross sections, plotted as the fractional difference $[d\sigma({}^3\mathrm{H})/d\Omega - 2d\sigma({}^3\mathrm{He})/d\Omega]/[d\sigma({}^3\mathrm{H})/d\Omega + 2d\sigma({}^3\mathrm{He})/d\Omega]$ as a function of angle, is shown in Fig. 2. This ratio is calculated in the PWIA using the model of Fearing as described above. The ^{3}H wave function was obtained by increasing the parameter α in the correlated cluster wave function by 4% to remove the Coulomb effects.[5] Equivalent values for α can be obtained by several methods.[15] Since this ratio is constant as a function of angle, the weighted average of the ratio can be obtained and is also shown in Fig. 2. Almost the entire value of this ratio comes from the change in the normalization constant between the ^{3}He and the ^{3}H wave functions.[15] The calculation is in good agreement with the data.

In summary, the angular distribution of the $pd \rightarrow {}^3\mathrm{He}\pi^0$ reaction at 800 MeV was measured between c.m. pion angles of 10° to 135°. It was observed that within experimental error the ratio of the cross section to the $pd \rightarrow {}^3\mathrm{H}\pi^+$ cross section is given by isospin and the difference in the ^{3}He and ^{3}H wave functions. The PWIA and DWIA calculations reproduce qualitatively the shape and the correct order of magnitude of the data, respectively. However, the calculation disagrees with the data in a detailed comparison, particularly at backward angles at this energy. While there is no minimum observed in the data due to the minimum in the three body form factor, wave functions which correctly include the high momentum components (including the D state in the deuteron wave function) clearly help the calculation. As has been pointed out, the problem may be due to the choice of energy used in the evaluation of the two body $pp \rightarrow d\pi$ amplitude. However, multistep processes may also begin to become important as one moves away from resonance, allowing, perhaps, the amplitude to be evaluated at a lower effective momentum transfer. This could resolve problems observed with both the absolute value and the shape of the calculation.

More precise information on wave functions and distortion effects for the DWIA calculation would be needed to clarify this matter. Measuring the reactions $pd \rightarrow {}^3\mathrm{He}\pi^0$ and $pd \rightarrow {}^3\mathrm{H}\pi^+$ at other energies in the energy region from 600 MeV to 1 GeV should give more insight as to how to overcome the theoretical uncertainties. In particular, polarization measurements and predictions would be extremely valuable. It is hoped this experiment will stimulate more interest in the (p,π) reaction on light nuclei at these energies.

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