Proton Polarization from π^+ Absorption in ^{3}He

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We present the first polarization measurements for pion absorption on a nucleus heavier than the deuteron. The polarization of protons resulting from π^+ absorption in ^{3}He was measured at bombarding energies of 120 and 250 MeV. Protons from absorption in a quasideuteron were selected by applying kinematical constraints. A significant discrepancy was observed between the experimental results and theoretical predictions. At 120 MeV the polarizations for ^{3}He are consistent with those of the deuteron. At 250 MeV the angular distribution of the polarization is significantly different than for the deuteron, showing sensitivity to the nuclear density, and thus may be sensitive to short range nucleon correlations.

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Much of the interest in short range ($r < 1$ fm) correlations between nucleons stems from the possibility of learning about the short range nucleon-nucleon interaction in the regime where non-nucleonic degrees of freedom may become relevant [1]. An experimental study of such correlations should have two important features: (1) requirement of the participation of at least two nucleons and (2) sensitivity to large-momentum components in the relative wave function of the two nucleons. Large-momentum-transfer scattering experiments like $(e,e'p)$ are sensitive to large-momentum components of *single* nucleon wave functions but do not require participation of two nucleons. Conversely, pion double-charge-exchange reactions require the participation of two nucleons but are not sensitive to large-momentum components in their relative wave function. The pion absorption process satisfies both requirements. It is a high-momentum transfer process (~ 350 MeV/c) which involves more than one nucleon and hence provides sensitivity to small relative distances between the absorbing nucleons (0.5–0.7 fm). The deuteron offers the simplest system on which a pion may be absorbed.

In principle, one could learn about the short range N-N correlations and their contribution to the pion absorption process by decreasing the internucleon distance, thereby enhancing the effect of the correlations. Although impossible in practice with real deuterons, such investigations are possible through the study of pion absorption on the "quasideuterons" which exist within a nuclear environment ($A \geq 3$). The size of this $T=0$ p-n pair is smaller than that of the real deuteron due to increased nuclear binding and the density of nucleons in ^{3}He is twice that of the deuteron [2].

The pion absorption process, however, is dominated by the p-wave pion rescattering diagram, in which pion absorption creates a Δ resonance in the intermediate state followed by the $\Delta N \to NN$ transition. This mechanism masks the N-N correlations. Indeed, cross-section measurements of π^+ absorption on ^{3}He and ^{4}He have shown no sensitivity to short range N-N correlations [3]. This follows from the observation that for all angles

$$\sigma(\pi^+ \text{"}d\text{"} \to pp) \cong N_{\text{"}d\text{"}} \sigma(\pi^+ d \to pp) , \qquad (1)$$

where $N_{\text{"}d\text{"}}$ is the number of quasideuterons in the nucleus.

A much smaller transition amplitude in the absorption process occurs through s-wave rescattering. Since this component is not mediated by the Δ resonance it can have the required sensitivity to short range nucleon correlations. As cross sections depend on the squares of amplitudes, such observables are insensitive to this component. Polarization observables, however, depend on interferences between amplitudes and so are particularly sensitive to the smaller terms.

In this work we present the first polarization measurements for pion absorption on a nucleus heavier than the deuteron. The polarization of one of the final-state protons in the $\pi\text{"}d\text{"} \to \vec{p}p$ reaction within the ^{3}He system was measured. The results can be compared with the free process for which this polarization is simply related to the extensively measured analyzing power A_{N0} of the time-reversed $\vec{p}p \to d\pi$ reaction. Differences between the free and quasifree processes should provide a useful tool for investigating short range nucleon-nucleon correlations.

Although meson exchange calculations reproduce the differential cross sections reasonably well for pion absorption on the deuteron, significant discrepancies exist between these calculations and polarization observables, especially at energies above the Δ resonance [4]. Part of this discrepancy may be due to sensitivity of the polarization to the poorly known short range correlations. An attempt to remedy these difficulties was made [5] by including a process where the pion is absorbed on a six-quark component in the deuteron wave function. While only modest success could be claimed, this was an interesting additional dimension in treating these problems. This approach was later applied to the process of pion absorption on the diproton [6], where the Δ resonance contributes insignificantly.

A theoretical investigation of pion absorption in ^{3}He has been carried out by Niskanen and Thomas [7]. In their treatment, the pion is considered to be absorbed on a quasideuteron with the role of the third nucleon being that of a spectator. The two-nucleon absorption was described in terms of the Helsinki model [8] which has been rather successful in describing the analyzing power of the $\vec{p}p \rightarrow d\pi$ reaction (and thus the polarization arising from π^+ absorption on the deuteron) for pion bombarding energies up to the Δ resonance. In describing the S state of the quasideuteron the authors used the correlation function given by Friar *et al.* ($\psi_{\rm qd}^{\rm RSC}$) [9], which was generated using the Reid soft-core potential. It was supplemented by a 10% D-state component. Results of additional calculations using the Faddeev-based Argonne-Urbana correlation function of Schiavilla *et al.* ($\psi_{\rm qd}^{\rm AU}$) [10] are also presented in this Letter (Table I and Fig. 2). The two correlation functions differ significantly in the short range region, the former showing strong short range repulsion. The theoretical polarizations were obtained as a function of detection angle for various pion bombarding energies. The results indicate a strong sensitivity to the form of the correlation functions employed with significant differences found between the expected polarization for absorption on the quasideuteron compared with that on the free deuteron.

The experiment was performed in the M11 channel at TRIUMF. Positive pions of 120 and 250 MeV were absorbed in both a liquid ^{3}He and a solid CD_2 target. The latter provided free deuterons for the $\pi d \rightarrow \vec{p}p$ reaction with which the system could be checked and calibrated [11]. Outgoing protons were detected in coincidence by a two-arm detection system. The two arms were positioned at the conjugate angles appropriate to pion absorption on the free deuteron. Some measurements were taken at nonconjugate angles in order to emphasize large values of momenta for the undetected nucleon. One arm consisted of a proton polarimeter and the second was an array of plastic scintillators. The polarimeter [11,12] consisted of two sets of three delay-line drift chambers each, with a carbon analyzer between them. The position resolution of the chambers was 0.3 and 0.6 mm for the front and back drift chambers, respectively. Thin scintillators were placed in front of and behind the last set of wire chambers and were used for triggering and time-of-flight (TOF) measurements. The second arm was a 1×1-m^2 detector array consisting of eight plastic scintillators, each 12.5 cm wide, 1 m high, and 10 cm deep. It was used for triggering and TOF measurements. Its position resolution was 12.5 cm (horizontal) and 6 cm (vertical). The TOF resolution of both arms was 0.5 nsec.

The polarization was calculated from the polar (θ) and azimuthal (ϕ) scattering angles in the carbon, deduced from the drift-chamber information, according to the polarization estimators method [13]. It is based on the relation

$$I(\theta,\phi) = I_0(\theta)[1 + A_y(\theta,E_p)\mathbf{P}_p \cdot \hat{\mathbf{n}}]A_c(\theta,\phi)\,, \qquad (2)$$

where $I(\theta,\phi)$ is the measured yield, $I_0(\theta)$ is the unpolarized scattering cross section. $\mathbf{P}_p$ is the proton polarization, and $\hat{\mathbf{n}}$ is the normal to the proton scattering plane. $A_y(\theta,E_p)$ is the analyzing power for proton-carbon scattering in the carbon analyzer. It depends both on the proton energy E_p and on the polar scattering angle θ [14]. $A_c(\theta,\phi)$ reflects the acceptance of the apparatus. A proton scattered by (θ,ϕ) was accepted only if the polarimeter could detect the azimuthally symmetric scattering at $(\theta,\phi+180°)$ in the fashion described by Besset *et al.* [13]. In order to select protons from pion absorption in ^{3}He we used the difference between the TOF measured to the array and the same but calculated from the TOF to the polarimeter and the two proton's detection angles. The calculation assumed kinematics of pion absorption in ^{3}He so events in the peak around zero difference (Fig. 1) belong to this process while the rest is background from other reactions. Only events in the peak were used for further analysis.

The polarization as a function of the momentum of the undetected particle (the recoil momentum) is shown in Fig. 2. Earlier differential cross-section studies indicated [15] that as long as $P_{\rm recoil} < 150$ MeV/c, the absorption process is dominated by the two-nucleon absorption mechanism. For this range of momenta the polarization was found to be a constant. At larger recoil momenta, where the third particle can no longer be regarded as a spectator and the three-nucleon absorption mechanism plays a more significant role, the value of the polarization drops. This trend was observed at all detection angles. We can therefore associate a single polarization value

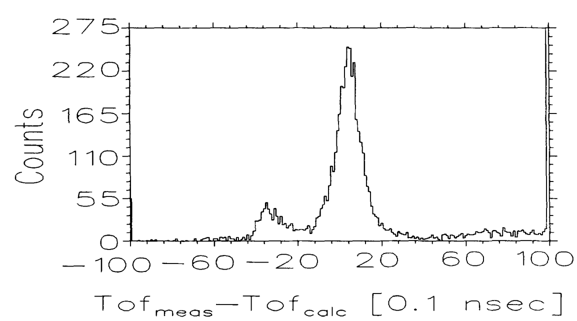

FIG. 1. Difference between the TOF measured to the detector array and the same but calculated using the TOF to the polarimeter and the two particle detection angles. The calculation assumed kinematics of pion absorption in ^{3}He.

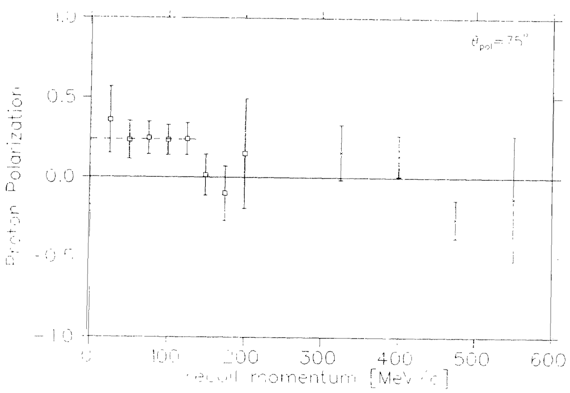

FIG. 2. Proton polarization as a function of the recoil momentum for π^+ absorption in ^3He at 250 MeV. The dashed line represents the average polarization for $P_{recoil} < 150$ MeV/c. The squares indicate the (quasideuteron) measurements at conjugate angles with 25-MeV/c bins, whereas the crosses are measurements at nonconjugate angles with 75-MeV/c bins, indicating the polarization characterizing "three-body" pion absorption.

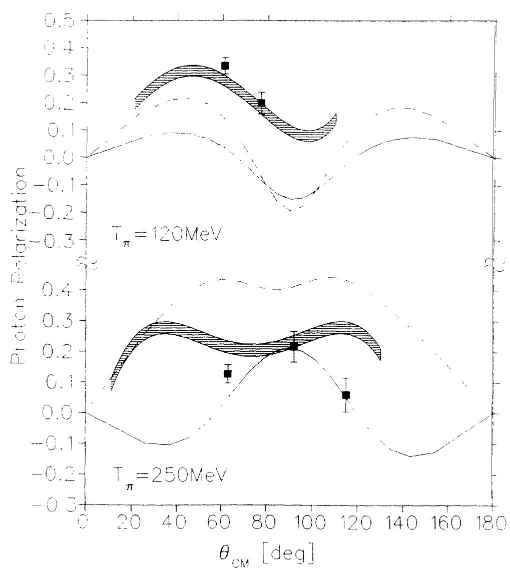

FIG. 3. Angular dependence of the proton polarization from π^+ absorption in ^3He at 120 and 250 MeV. The solid lines are the theoretical predictions using the ψ_{qd}^{AU} correlation function, whereas the dashed lines are the results of Niskanen and Thomas [7] based on ψ_{qd}^{RSC}. The bands represent values of the polarization for the free deuteron, and are extracted from fits to the analyzing powers measured for the inverse reaction [16]. The width of the band represents the experimental uncertainties. The measured polarization results are marked by squares with error bars.

with quasideuteron absorption by using only the subset of data corresponding to recoil momenta < 150 MeV/c. This matches the requirement made in the theoretical calculations that the third nucleon be treated as a spectator.

The measured deuteron and quasideuteron polarization results are listed in Table I. Also listed are values of the polarizations obtained from previous measurements of analyzing powers of the $\vec{p}p \rightarrow d\pi$ reaction [16], together with the polarizations predicted using the different correlation functions. The errors shown include both statistical and systematic errors. Systematic errors can arise as a result of errors either in the TOF calibrations of the scintillators or the trajectory coordinates extracted from the drift-chamber outputs. Errors in such position measurements could cause systematic errors in the acceptance check and in both θ and ϕ, and, as a result, in the value of A_y employed. As the values for A_y are obtained from previous measurements, they involve uncertainties which can be regarded as an additional source of systematic error. Errors in the TOF measurements, which imply erroneous values for the proton energy, would also impact on the value used for the proton-carbon analyzing power. The magnitude of the systematic error applicable to the polarization measurements was estimated by varying these parameters within the measured resolution and observing the effect of their variation on the results. The resulting systematic errors which were comparable in magnitude to the statistical errors were added in quadrature to the statistical errors to obtain the final errors listed in Table I. More detailed discussion of the uncertainties can be found elsewhere [17].

Polarization measurements on the free deuteron were performed as a check of the apparatus. Rather than one long measurement several short ones with poorer statistics were made at a few points. Out of four measurements three are within 1 standard deviation (σ) and the fourth is within 1.5σ of previous results, and there are no systematic deviations. The results are therefore consistent with the previous measurements.

Figure 3 shows the angular distributions of the predict-

TABLE I. Proton polarization from π^+ absorption in deuterium and ^3He.

		$P_N(\pi^+ d \rightarrow \vec{p}p)$		$P_N(\pi^+ {}^3He \rightarrow (\vec{p}p)p)$		
T_π (MeV)	$\theta_{c.m.}$ (deg)	This measurement	Previous measurement	This measurement	Prediction using ψ_{qd}^{RSC}	Prediction using ψ_{qd}^{AU}
250	63	0.19(0.05)	0.23(0.02)	0.13(0.03)	0.43	0.06
	92	0.32(0.04)	0.25(0.02)	0.22(0.05)	0.41	0.21
	115	···	0.26(0.02)	0.06(0.06)	0.42	0.05
120	61	0.31(0.03)	0.31(0.02)	0.34(0.03)	0.09	0.0
	77	0.14(0.04)	0.18(0.02)	0.20(0.04)	−0.16	−0.14

ed polarization for π^+ absorption on ^{3}He at pion bombarding energies of 120 and 250 MeV, together with the experimental results. Also shown are the previously measured results from the inverse reaction $\vec{p}p \rightarrow d\pi$. As seen in the table and shown in Fig. 3, the polarization measurements for 120-MeV pions on ^{3}He yield values similar to the previously measured analyzing powers for the deuteron. The measurements with 250-MeV pions result in a polarization angular distribution very different from that of the deuteron. Contrary to the experimental results the theoretical predictions differ much more markedly between the two energies. At 120 MeV, both of the correlation functions used in the theoretical work yield polarization values significantly *lower* than that for the free deuteron, whereas at 250 MeV use of ψ_{qd}^{RSC} yields values *larger*, while the predictions based on ψ_{qd}^{AU} remain *less* than for the the free deuteron. Interestingly, the angular dependence of the experimental results at 250 MeV is more similar to that produced by the ψ_{qd}^{AU} rather than ψ_{qd}^{RSC}. The observed difference between the angular distribution for deuteron and quasideuteron in ^{3}He at 250 MeV may indicate a sensitivity to nuclear density. The connection to short range correlations is seen from the sensitivity of the calculations to the choice of the correlation function. It may also indicate an increased influence of three-nucleon absorption mechanisms observed [15] to be larger at higher energies. Still, more theoretical work is required before meaningful conclusions can be deduced. In particular, the theoretical investigations should include a more detailed treatment of initial- and final-state interactions than that characterizing the existing calculations [7]. More extensive use of Faddeev wave functions should also be applied to the ^{3}He nucleus.

Since the work reported here was the first of its kind, only a limited amount of data were obtained and this at only two pion energies, one below and one above the Δ resonance. Now that significant effects have been demonstrated, additional measurements should be performed in order to provide a more complete set of data, with polarizations measured at more angles and at additional pion bombarding energies. Measurements of other spin observables are also underway for this reaction [18,19]. Extension of both experiment and theory to other light nuclei (such as ^{4}He [20]) would provide valuable additional "density-dependent" information. Through the development of such a program, we can hopefully look forward to a more comprehensive understanding of the role of short range correlations in pion absorption.

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