Measurement of Quasielastic ^{3}He$(\vec{p}, pN)$ Scattering from Polarized ^{3}He and the Three-Body Ground State Spin Structure

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We report measurements of spin correlations and analyzing powers in $^3\overrightarrow{\mathrm{He}}(\vec{p}, 2p)$ and $^3\overrightarrow{\mathrm{He}}(\vec{p}, pn)$ quasielastic scattering as a function of momentum transfer and missing momentum at 197 MeV using a polarized internal target at the Indiana University Cyclotron Facility Cooler Ring. At sufficiently high momentum transfer we find $^3\overrightarrow{\mathrm{He}}(\vec{p}, pn)$ spin observables are in good agreement with free p-n scattering observables, and therefore that $^3\overrightarrow{\mathrm{He}}$ can serve as a good polarized neutron target. The extracted polarizations of nucleons in $^3\overrightarrow{\mathrm{He}}$ at low missing momentum are consistent with Faddeev calculations.

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The ^{3}He nucleus is the subject of considerable current interest. It is a calculable nuclear system where our understanding of nuclear structure can be precisely compared with data. In addition, it is generally thought that polarized ^{3}He can serve as an effective polarized neutron target for experiments in nuclear [1] and particle [2] physics. Fundamental properties of the neutron such as its charge and spin distributions remain largely unconstrained experimentally. Thus, many experiments using polarized ^{3}He targets are underway worldwide in large part motivated by measurement of neutron elastic form factors [3–5] and deep inelastic structure functions [6–8]. It is imperative to understand the ground state spin structure of the ^{3}He nucleus to extract information on neutron structure from these measurements.

Nonrelativistic Faddeev calculations [1,9] of the three-body bound state predict the following components to dominate the ^{3}He ground state wave function: (a) a spatially symmetric S state, accounting for $\sim 90\%$ of the spin-averaged wave function, has the ^{3}He spin entirely due to the neutron with the two protons in a spin singlet state; (b) a D state due to the tensor force accounts for $\sim 8\%$ of the spin-averaged wave function and has the three nucleon spins dominantly oriented opposite to the ^{3}He nuclear spin; (c) a mixed-symmetry configuration of the nucleons, the S' state, arises from spin-momentum correlations [10] and accounts for $\sim 2\%$ of the spin-averaged wave function. All other components are predicted to be negligibly small.

The nuclear structure information is contained in the spin-dependent spectral function [11] $S^N_{\hat\sigma}(E, \mathbf{p})$ defined as the probability density of finding a nucleon N with separation energy E, momentum $\mathbf{p}$, and spin along (opposite) the $^3\overrightarrow{\mathrm{He}}$ spin indicated by $\hat\sigma = +\ (-)$. In the nonrelativistic approximation using Faddeev techniques, the S- and S'-state contributions to the spectral function are found to be maximum for $p = 0$, while the D-state contribution is greatest for larger momenta [1,9].

Quasielastic spin-dependent knockout of the constituent nucleons of ^{3}He offers the most direct experimental approach to constrain the spectral function. An incident polarized proton of 4-momentum $\mathbf{P}_{\mathrm{inc}} \equiv (T_{\mathrm{inc}} + M; \mathbf{p}_{\mathrm{inc}})$ scatters from a nucleon in ^{3}He resulting in a proton with $\mathbf{P}_1 \equiv (T_1 + M; \mathbf{p}_1)$ and a second nucleon with $\mathbf{P}_2 \equiv (T_2 + M; \mathbf{p}_2)$. In the plane wave impulse approximation (PWIA) the two nucleons are ejected without secondary scattering from the residual nucleus implying that we can identify the missing momentum $\mathbf{p}_{\mathrm{m}} \equiv \mathbf{p}_{\mathrm{inc}} - \mathbf{p}_1 - \mathbf{p}_2$ with the initial momentum of the struck nucleon, $\mathbf{p}$. The recoil system is either a deuteron (two-body breakup) or two unbound nucleons (three-body breakup) and in PWIA the missing energy, $E_m \equiv T_{\mathrm{inc}} - T_1 - T_2 - T_{\mathrm{recoil}}$, is identified with the separation energy.

The spin-dependent differential cross section with both beam and target spins oriented normal to the scattering plane can be written as [12]

$$\sigma = \sigma_0(1 \pm P_b A_{00n0} \pm P_t A_{000n} + P_b P_t A_{00nn}), \qquad (1)$$

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where P_b and P_t are the polarizations of the beam and target, the + and − distinguish between beam left and right regions of the scattering plane, σ_0 is the unpolarized cross section, A_{00nn} is the spin-correlation parameter, and A_{00n0} and A_{000n} are the beam and target analyzing powers, respectively. In PWIA we relate the target spin observables $A_{00in}^{3,N}$ ($i = 0$ or n) for $^3\mathrm{He}(p,pN)$ scattering (N is a proton p or neutron n) to the $N(p,p)$ elastic scattering observables, A_{00in}^{N}, extracted from phase shift analyses [13] and the spectral functions S_{σ}^{N}, by

$$A_{00in}^{3,N} = A_{00in}^{N} \cdot P^n \quad \text{and} \quad P^N = \frac{S_+^N - S_-^N}{S_+^N + S_-^N}, \qquad (2)$$

where P^N is a function of p_m and E_m and is interpreted as the polarization of a nucleon in ^{3}He. Comparisons [14] of unpolarized $(p,2p)$ and $(e,e'p)$ data indicate that rescattering effects of initial and final state nucleons may be large at high p_m, so our focus will be on the low p_m data. In addition, the Faddeev calculations predict little influence of the D state at low p_m so that $P^n = 1$ and thus spin observables consistent with free scattering should be observed if PWIA holds.

Previous measurements of spin dependent $^3\overrightarrow{\mathrm{He}}(\vec{p},2p)$ and $^3\overrightarrow{\mathrm{He}}(\vec{p},pn)$ quasielastic scattering at 220 [15] and 290 MeV [16,17] incident energies disagreed significantly with PWIA calculations. In particular, $A_{000n}^{3,n}$ was observed to be strongly suppressed. These experiments were carried out for small proton scattering angles (27.5° at 290 MeV, 34° at 220 MeV), i.e., low momentum transfer with relatively small acceptance in angle and p_m. In contrast, the experiment described here measured asymmetries over a wide range of scattering angles (21°–67°), i.e., from low to high momentum transfer, and over an extended range in p_m by making use of large acceptance detectors.

The experiment was performed at the Indiana University Cyclotron Facility (IUCF) Cooler Ring [18] using a polarized ^{3}He internal target [19]. Details of the experiment beyond those given below will be published elsewhere [20]. The target and beam were polarized normal to the scattering plane and data were acquired at a beam energy of 197.5 ± 0.1 MeV. Figure 1 shows a schematic layout of the experimental apparatus. A large acceptance detector arm was located on each side of the target to detect two nucleons in coincidence, one on each side of the beam. Each arm consisted of a set of 300 μm silicon microstrip detectors (SDL,R), a 3 mmm thick ΔE plastic scintillator, two pairs of wire chambers (WC), six $100 \times 10 \times 5$ cm^3 scintillator E bars with a neutron efficiency of ~15%, and an additional 9.5 cm thick plane of plastic scintillators (BPL,R). At regular intervals H_2 was flowed in the target and $^1\mathrm{H}(p,2p)$ measurements were taken to calibrate the time-of-flight system, monitor the stability of the electronics, determine the kinematic resolutions, and provide information on the background rate. From these calibrations it was determined that the time-of-flight resolutions (FWHM) was ~2 ns, the p_m resolution (FWHM) was 30 MeV/c, the E_m resolution (FWHM) was 20 MeV, and the background rate of scattered events from material other than polarized ^{3}He was below 1%,

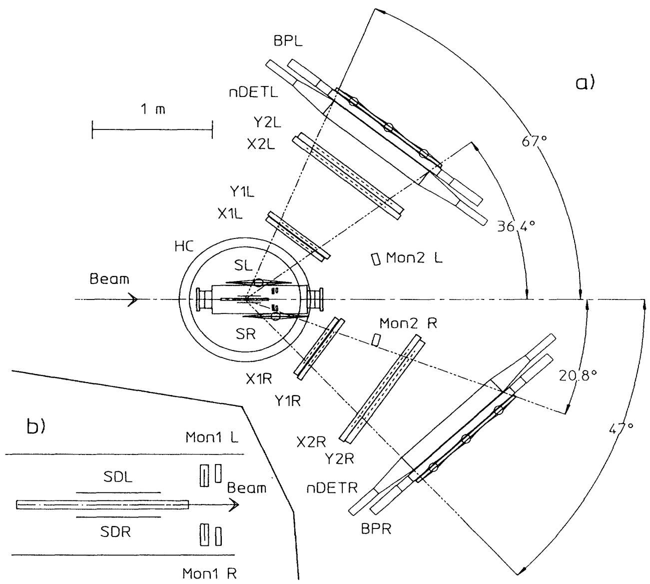

FIG. 1. Schematic layout of the experimental apparatus.

The stored beam intensity varied from 100 to 50 μA with a lifetime of ~1000 s in the presence of target gas. The target [21] had an average polarization of 0.46 with normalization uncertainty of ±0.02 and a thickness of 1.5×10^{14} atoms/cm^2 resulting in a typical luminosity of 6×10^{28} cm^{-2} s^{-1}. The average beam polarization was 0.72 with a normalization uncertainty of 0.01. The target polarization was reversed every 180 s independent of the beam status. The beam polarization was reversed before each injection. The relative integrated luminosity versus spin state was needed to extract the spin observables from the yields and was monitored by two independent schemes. In the first, the target thickness was monitored by measuring the input ^{3}He gas pressure and the circulating beam current was measured with a parametric current transformer [22]. In the second, the relative luminosity and beam and target polarization were monitored by detecting elastically scattered protons at forward angles with scintillators (Mon1,2;L,R) in coincidence with the recoiling ^{3}He nuclei in the silicon detectors (SDL,R). These monitor data were taken simultaneously with the quasielastic data. An unpolarized hydrogen target and associated detector system [23], located at another site in the ring, was periodically operated concurrently with the main setup to calibrate the spin dependence of the luminosity and polarization monitor. The two methods of monitoring the luminosity agreed to within 1%.

The $^3\mathrm{He}(p,pN)$ data were analyzed by reconstructing a proton track from the measured wire chamber information and determining the vertex of the event. A proton triggered both ΔE and E counters and fired all wire chambers. Protons were separated from other charged particles by particle identification correlations between energy deposition and time of flight. A $^3\mathrm{He}(p,2p)$ event had a proton trigger in each arm, while a $^3\mathrm{He}(p,pn)$ event had a proton trigger in one arm and a coincidence event in the second arm which fired the E counter but neither the ΔE counter or the wire chambers. The neutron path length was reconstructed using the position at the E bar, determined from the bar hit and the difference in photon pulse arrival time at each end of the scintillator bar, and the vertex obtained from the proton arm. The energy of both nucleons was extracted from the time of flight, thus allowing full reconstruction of their momentum vectors.

Data were taken in all possible polarization combinations (up, down, unpolarized) of beam and target. For data with both the beam and target polarized, the events were sorted into the four possible polarization combinations. The yields were corrected for luminosity and deadtime in each combination and then the four simultaneous equations generated from Eq. (1) were solved to extract the three $A_{00ij}^{3,N}$ and the unpolarized cross section with associated uncertainties. Data taken with either the beam or target unpolarized gave values consistent with those extracted from the doubly polarized data.

The spin observables were extracted as a function of various kinematic variables for both $^3\mathrm{He}(p,2p)$ and $^3\mathrm{He}(p,pn)$ reactions. The beam and target analyzing powers in $^3\mathrm{He}(p,pn)$ scattering should be equal in the limit $p_m \rightarrow 0$, if corrections to the PWIA are small. $A_{00n0}^{3,n}$ and $A_{000n}^{3,n}$ for $p_m < 100$ MeV/c are shown as a function of the magnitude of the 3-momentum transfer $|\mathbf{q}|$ of the struck neutron in Fig. 2. For data with $|\mathbf{q}| > 500$ MeV/c we find that the neutron polarization, extracted by calculating the ratio of target to beam analyzing power, is $0.94 \pm 0.08 \pm 0.12$, where the errors are statistical and systematic (polarization plus luminosity uncertainties), respectively. This result is consistent with PWIA and the full polarization predicted by the Faddeev calculations. In contrast, at low momentum transfer there is a sizable deviation between the two observables, in agreement with the TRIUMF data [15–17] taken at $|\mathbf{q}| \sim 370$ MeV/c. We interpret this $|\mathbf{q}|$ dependence as evidence of a significant spin-dependent final-state interaction of the recoiling neutron for low momentum transfer. Such an effect has been predicted in calculations of spin-dependent quasielastic $(e,e'n)$ scattering [24]. As in the TRIUMF measurements, the present $(p,2p)$ observables were found to be consistent with expectations from the Faddeev calculations and PWIA.

The good agreement between $A_{000n}^{3,n}$ and $A_{00n0}^{3,n}$ at high momentum transfer indicates we can investigate the polarization of the nucleons, again at low missing momentum, by applying the PWIA model of Eq. (2) to the spin correlation data. Figure 3 shows (a) $A_{00nn}^{3,n}$ for protons scattered to the left detector, and (b) $A_{00nn}^{3,p}$ as a function of p_m for $|\mathbf{q}| > 500$ MeV/c. The shaded boxes at $p_m = 0$ represent the range of PWIA predictions from a Monte Carlo calculation including the experimental acceptance and momentum resolutions for a number of phase shift solutions extracted from SAID [13] for $|\mathbf{q}| > 500$ MeV/c

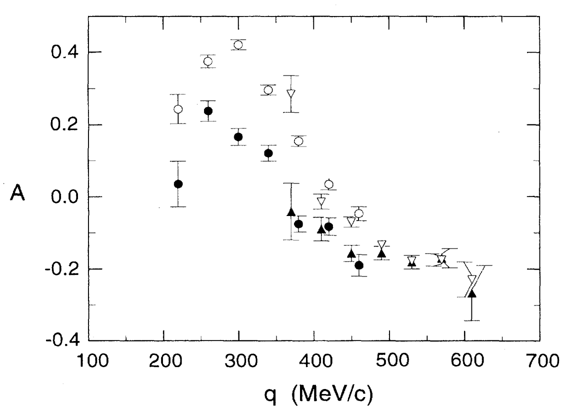

FIG. 2. The target (filled symbols) and beam (open symbols) analyzing powers, $A_{000n}^{3,n}$ and $A_{00n0}^{3,n}$, respectively, for $^3\mathrm{He}(p,pn)$ at $|p_m| > 100$ MeV/c as a function of the 3-momentum transfer to the struck neutron $|\mathbf{q}|$. Data where the proton scattered to the right (left) detector and neutrons to the left (right) detector are indicated by circular (triangular) symbols.

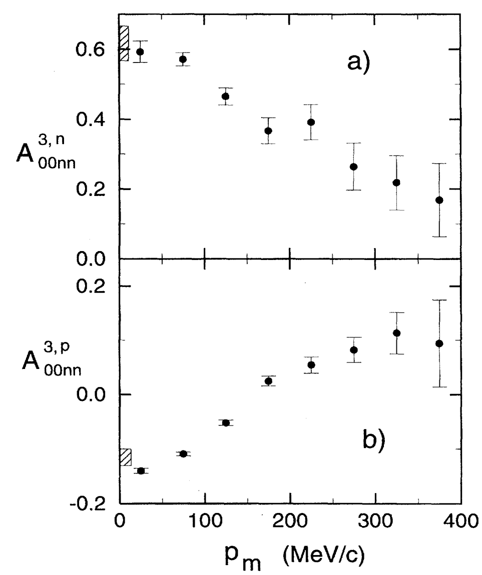

FIG. 3. The missing momentum distribution of (a) $A_{00nn}^{3,n}$ in $^3\mathrm{He}(p,pn)$ for $|q| > 500$ MeV/c, (b) $A_{00nn}^{3,p}$ in $^3\mathrm{He}(p,2p)$. The error bars reflect only the statistical errors. In addition there is an error band of ± 0.03 due to luminosity uncertainties. The shaded boxes in each panel at $p_m = 0$ indicate the range of PWIA predictions allowed by various phase shift solutions for the free observables.

and are in good agreement with the data. We use Eq. (2) and the free scattering observables to extract the polarization of the nucleons at low p_m and find $P^n(p_m = 0) = 0.98 \pm 0.06 \pm 0.05 \pm 0.08$, in good agreement with the polarization extracted from the analyzing powers, and $P^p(p_m = 0) = -0.16 \pm 0.01 \pm 0.03 \pm 0.02$. Here the first uncertainty is the statistical error from fitting a third order polynomial to the data for the extrapolation to $p_m = 0$, the second is systematic errors (polarization plus luminosity uncertainties), and the third represents the range of predictions for the free scattering observables from various phase shift analyses and uncertainties in the Monte Carlo modeling. The Monte Carlo calculation uses the spin-dependent spectral function of [9] and predicts $P^n(p_m = 0) = 1.00$ and $P^p(p_m = 0) = -0.12$, in good agreement with our results. In this calculation the full polarization of the neutrons reflects the dominance of the S state and the small polarization of the protons reflects the effects of the S' state, both at low p_m.

In conclusion, we have measured quasielastic $^3\overrightarrow{\mathrm{He}}(\vec{p},2p)$ and $^3\overrightarrow{\mathrm{He}}(\vec{p},pn)$ scattering at 197 MeV incident energy and extracted the p_m dependence of the spin observables. A large acceptance detector was central to our ability to unravel the puzzle remaining from the previous experiments by allowing a survey of a wide range of kinematics, thus allowing the separation of effects due to the reaction mechanism from those due to ground state structure. The observables at low p_m are well described by the PWIA model in kinematics where the momentum transfer to the struck neutron is large. These results imply that extraction of neutron elastic form factors with $(e,e'n)$ measurements may not be reliable at low Q^2, which is consistent with previous calculations [24]. We have determined that the polarization of the neutron and protons at $p_m = 0$ in ^{3}He are in good agreement with Faddeev calculations. The data at higher p_m agree qualitatively with the trends expected from the spectral functions. However, these data are not analyzed quantitatively here as previous measurements [14] indicate rescattering effects are expected to be large at higher p_m. We hope these data encourage more extensive calculations. In addition, these results provide strong motivation to proceed with measurements of spin-dependent electromagnetic observables at intermediate energies on the ^{3}He nucleus [5,25] where a weakly interacting probe should allow the extraction of information sensitive to the ground state structure (e.g., D-state effects) for $p_m > 0$.

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