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The spin dependent momentum distributions of the neutron and proton in ^{3}He

R.G. Milner[c], C. Bloch[a], J.F.J. van den Brand[d], H.J. Bulten[d], D. DeSchepper[c], T.W. Donnelly[c], R. Ent[c,1], C.D. Goodman[a], J.-O. Hansen[c,2], W.W. Jacobs[a], C.E. Jones[d,2], W. Korsch[c,3], L.H. Kramer[c], K. Lee[c], M. Leuschner[a], W. Lorenzon[g,4], N.C.R. Makins[c,2], D. Marchlenski[e], H.O. Meyer[a], M. A. Miller[d,5], J.S. Neal[d], P.V. Pancella[f], S.F. Pate[c,6], W.K. Pitts[b], B. von Przewoski[a], T. Rinckel[a], P.U. Sauer[h], G. Savopulos[a], R.-W. Schulze[h], A. Smith[a], J. Sowinski[a], F. Sperisen[a], E.R. Sugarbaker[e], M.A. Titko[c], C. Tschalär[c], O. Unal[d], T.P. Welch[c,7], Z-L. Zhou[d]

[a] *Indiana University Cyclotron Facility, Bloomington, IN 47405, USA*
[b] *University of Louisville, Louisville, KY 40292, USA*
[c] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[d] *University of Wisconsin-Madison, Madison, WI 53706, USA*
[e] *The Ohio State University, Columbus, OH 43210, USA*
[f] *Western Michigan University, Kalamazoo, MI 49007, USA*
[g] *TRIUMF, British Columbia, Canada V6T 2A3*
[h] *Institute for Theoretical Physics, University of Hannover, 30167 Hannover, Germany*

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Abstract

The spin asymmetries in the momentum distributions of the neutron and proton in ^{3}He are obtained from a Faddeev calculation of the ground state. Both two- and three-body configurations are found to be important. Using a PWIA model and measurements of the spin asymmetries in $^3\overrightarrow{\mathrm{He}}(\overrightarrow{\mathrm{p}},2\mathrm{p})$ and $^3\overrightarrow{\mathrm{He}}(\overrightarrow{\mathrm{p}},\mathrm{pn})$ quasielastic scattering at 197 MeV the asymmetries in the momentum distributions are experimentally determined. Good agreement between theory and experiment is found up to initial nucleon momenta of 300 MeV/c.

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[1] Present address: CEBAF, Newport News, VA 23606, USA.
[2] Present address: Argonne National Laboratory, Argonne, IL 60439, USA.
[3] Present address: Caltech, Pasadena, CA 91125, USA.
[4] Present address: University of Pennsylvania, Philadelphia, PA 19104, USA.
[5] Present address: University of Illinois, Urbana-Champaign, IL 61801, USA.
[6] Present address: New Mexico State University, Las Cruces, NM 88003-0001, USA.
[7] Present address: Oregon State University, Corvallis, OR 97331-6507, USA.

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1. Introduction

The ^{3}He nucleus has several properties which make the study of its spin particularly interesting. The three-body system is unique in that, although it is relatively tightly bound, essentially exact Faddeev solutions in non-relativistic approximations of the ground state have been obtained using a variety of two-nucleon potentials. In addition, unlike a heavy nucleus where the total spin is usually determined by only a few valence nucleons, the spin of ^{3}He involves all the nucleons in the nucleus. Further, Faddeev calculations predict that the ground state spin of the ^{3}He nucleus is dominated by the neutron. This property has motivated great interest in the use of polarized ^{3}He as an effective polarized neutron and targets suitable for scattering experiments have been constructed [1]. Recently, several significant measurements on the polarized ^{3}He nucleus have been carried out [2–6]. In addition, the spin-dependent spectral function, calculated from a Faddeev solution to the ^{3}He ground state, has become available [7].

It is predicted from non-relativistic Faddeev calculations of the three-body bound state [7,8] that three contributions dominate the ^{3}He ground state wave function: a) a dominant spatially symmetric S-state where the ^{3}He spin is entirely due to the neutron with the two protons in a spin singlet state; b) a D-state where the three nucleon spins are dominantly oriented opposite to the ^{3}He nuclear spin; c) a mixed-symmetry configuration of the nucleons, the S'-state. All other components are expected to be negligibly small. In the non-relativistic approximation using Faddeev calculations, the S and S' state contributions to the spectral function are expected to be a maximum for small nucleon momentum while the D-state contribution is greatest for larger momenta.

The nuclear spin of ^{3}He results from the sum of the spins of its individual nucleons and the angular momentum between them. Given the worldwide interest in polarized ^{3}He as an effective polarized neutron target for scattering experiments, it is important to experimentally measure the polarizations of the neutron and proton as a function of nucleon momentum.

2. The spin-dependent momentum distribution

The nuclear structure information is contained in the spin-dependent spectral function $S_{\hat{\sigma}_A}(E, \mathbf{p}, \mathbf{t})$ defined as the probability density of finding a nucleon N of isospin t with energy E, momentum $\mathbf{p}$ and spin σ_N parallel (antiparallel) to the $^3\overrightarrow{\mathrm{He}}$ spin indicated by $\sigma_A = +(-)$, where the kinematics are defined in Ref. [7]. The spectral function has the general form [7]

$$S_{\sigma_A}(E, \mathbf{p}, t) = \frac{1}{2}\{f_0(E,p,t) + f_1(E,p,t)\sigma_N \cdot \sigma_A + f_2(E,p,t)[(\sigma_N \cdot \hat{\mathbf{p}})(\sigma_A \cdot \hat{\mathbf{p}}) - \tfrac{1}{3}\sigma_N \cdot \sigma_A]\}. \quad (1)$$

The spin-averaged contribution f_0 and the two spin-dependent contributions f_1 and f_2 are scalar functions which depend only on the magnitude of $\mathbf{p}$. The effects of the Coulomb interaction have been neglected. The spectral function describes the spin structure of the ^{3}He nuclear ground state. Thus, it is an essential ingredient in the theoretical description of scattering from polarized ^{3}He. In quasielastic scattering experiments (both inclusive and exclusive) it characterizes the spins of the nucleons. In addition, it is an essential ingredient in the description of polarized ^{3}He as an effective polarized neutron in spin-dependent deep inelastic scattering at high energies. Convolution model calculations [9,10] require the light cone momentum distribution, which is constructed from the ground state spin-dependent spectral function.

The purpose of this Letter is twofold: First we present a calculation of the spin asymmetry in the momentum distribution of the neutron and proton in ^{3}He. Second, we extract the spin asymmetries in the momentum distribution from measurements of quasielastic polarized proton scattering from ^{3}He and compare the results with the calculations.

The momentum distribution for a nucleon of isospin t with spin parallel (anti-parallel) to the nuclear spin is defined as

$$\rho_{\uparrow(\downarrow)}(p,t) \equiv \int dE\, S_{\sigma_A=+(-)}(E,p,t)\,. \quad (2)$$

To make a direct connection with experiment, it is useful to define the spin asymmetry in the momentum distribution as

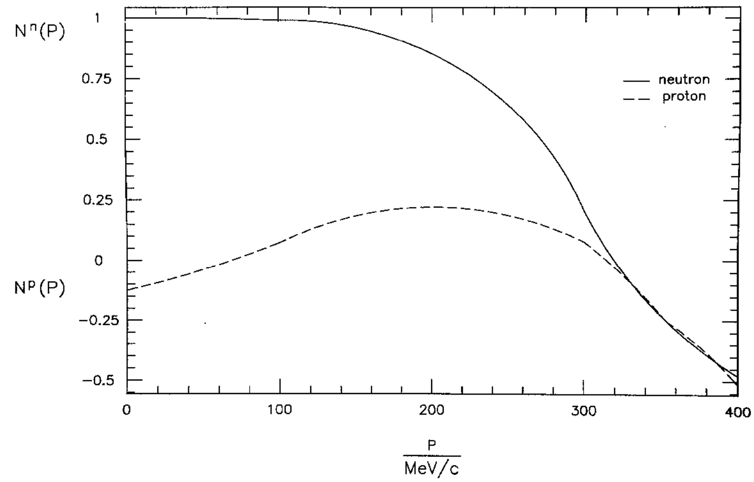

Fig. 1. The spin asymmetry in the momentum distribution of the neutron (solid line) and the proton (dashed line) plotted vs. nucleon momentum p.

$$N^t(p) \equiv \frac{\rho_\uparrow(p,t) - \rho_\downarrow(p,t)}{\rho_\uparrow(p,t) + \rho_\downarrow(p,t)}. \quad (3)$$

$N^t(p)$ is plotted for each nucleon isospin state in Fig. 1. In this calculation the Paris nucleon-nucleon interaction has been assumed. Note that the spin-averaged spin-dependent momentum distribution is the unpolarized momentum distribution which has been determined from unpolarized experiments in quasielastic kinematics.

In simplest approximation, an unbound neutron in ^{3}He can exist only in a state where the two protons are also unbound (the three-body configuration.) However, the proton in ^{3}He can be found in a state where the other nucleons form a deuteron (the two-body configuration) or as individual nucleons (the three-body configuration) as observed directly in quasielastic ^{3}He(e,e′p) scattering [11]. In Fig. 2 both two- and three-body contributions and the sum are shown for the proton. Physically, the distributions in Figs. 1 and 2 can be interpreted as the probability that a neutron or proton in ^{3}He has its spin directed parallel to the nuclear spin as a function of the nucleon momentum. Thus, the neutron in Fig. 1 at low p has its spin completely parallel to the nuclear spin but at high p, where the D-state is sizable, the neutron spin can be found with large probability directed opposite to the nuclear spin. In the case of the proton, from Fig. 2 it can be seen that the individual two- ($N_2^p(p)$) and three-body ($N_3^p(p)$) contributions to the total proton spin dependent momentum distribution are sizable and of opposite sign. (Note that even in the pure S-state $N_3^p(p=0) = -N_2^p(p=0) \approx 0.25$.) The addition of the S'-state yields for the complete wave-function $N_2^p(p=0) + N_3^p(p=0) = -0.12$. As with the neutron, at high p the presence of the D-state causes the proton spin to be predominantly directed opposite to the nuclear spin. The spin asymmetries in the momentum distribution were also calculated for the Bonn and Reid soft core nucleon-nucleon potentials with essentially identical results.

Quasielastic spin-dependent knockout of the constituent nucleons of ^{3}He with good resolution in the energy and momentum of the initial state nucleon offers the most direct experimental approach to constrain the spectral function. See [6] for a definition of kinematic variables: the missing momentum $\mathbf{p_m}$ in plane wave impulse approximation (PWIA) [12] can be identified with the negative of the the initial momentum of the struck nucleon. If PWIA is a good approximation to the scattering process, then information on the spectral function can be directly extracted.

3. Experimental determination of the spin asymmetry in the momentum distribution

The spin asymmetries in the momentum distributions can be determined by spin-dependent quasielas-

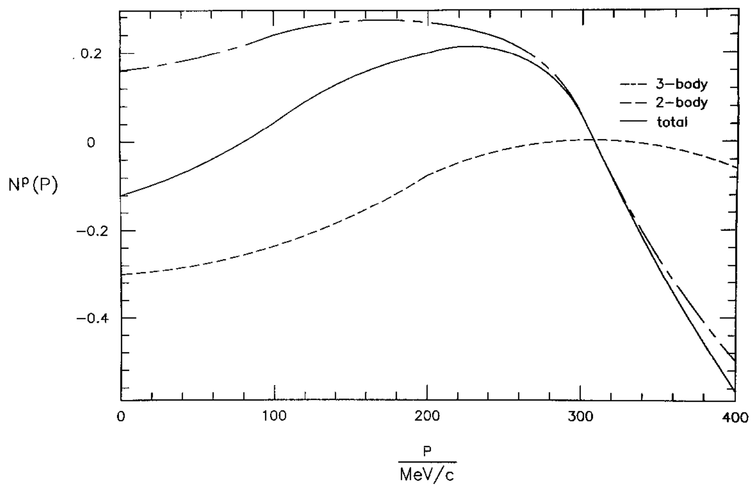

Fig. 2. The two-body contribution (dashed), the three-body contribution (dot-dashed) and the total (solid) proton spin asymmetry in the momentum distribution plotted vs. p.

tic knockout of the neutron and proton from a polarized ^{3}He target at intermediate energies with sufficient momentum and energy resolutions. As previously reported [6,15,16], we have carried out measurement of spin-dependent quasielastic knockout of the neutron and protons in ^{3}He using a 197 MeV polarized proton beam at the Indiana University Cyclotron Facility (IUCF) Cooler Ring. In this Letter we extract the spin asymmetry in the momentum distribution of the neutron and proton in ^{3}He by applying the PWIA model to the kinematic region where beam and target analyzing powers are in good agreement.

To understand the extraction of the spin asymmetries in the momentum distributions it is necessary to briefly consider the IUCF measurement. The spin-dependent differential cross section with both beam and target spins oriented normal to the scattering plane can be written as [13]

$$\sigma = \sigma_0 (1 \pm P_b A_{00n0} \pm P_t A_{000n} + P_b P_t A_{00nn}) , \quad (4)$$

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 the target spin observables $A^{3,N}_{00in}$ (i=0 or n) for ^{3}He(p,pN) scattering (N is a proton p or neutron n) can be related to the N(p,p) elastic scattering observables, A^N_{00in}, extracted from phase shift analyses [14], by

$$A^{3,N}_{00in} = A^N_{00in} \cdot N^t(p_m) , \quad (5)$$

where $N^t(p_m)$ is the spin asymmetry in the momentum distribution defined in (3) above.

A PWIA Monte Carlo model of quasielastic nucleon knockout by 197 MeV polarized protons has been constructed. In this model the nucleons are assumed to be on-shell structureless particles. The nucleon-nucleon spin-dependent scattering asymmetries are taken from the SAID parametrization [14]. The spin-dependent spectral function is that of Schultze and Sauer [7]. The experimental acceptances and resolutions are included in the model. As described in an earlier publication [6], the region of applicability of the PWIA for ^{3}He(p,pn) has been determined by demanding that $A^{3,n}_{000n} = A^{3,n}_{00n0}$. This has been observed to limit the kinematics to where the momentum transfer to the neutron is greater than 500 MeV/c. PWIA has been assumed to be valid for all kinematics for ^{3}He(p,2p). Using Eq. (5) above we have applied the PWIA model and extracted the spin asymmetries in the momentum distribution $N^N(p)$ for the neutron and proton respectively. The results are shown in Fig. 3 and compared with the PWIA model. The limits of the PWIA model for different nucleon-nucleon phase shifts and experimental resolutions are given by the solid curves. Good agreement is observed between the data and the model

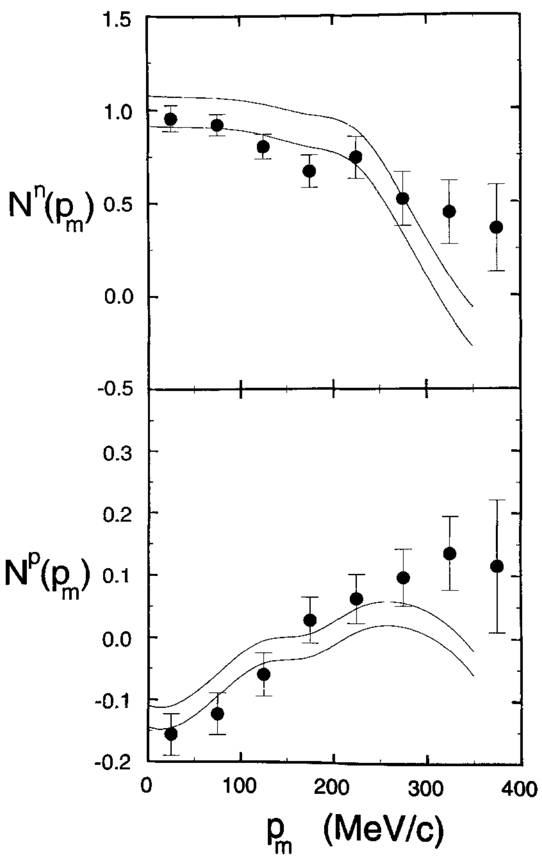

Fig. 3. The experimentally determined spin asymmetry in the momentum distribution of the neutron (upper panel) and the proton (lower panel) in the ^{3}He nucleus. The solid curves indicate the limits of the PWIA model.

prediction out to 300 MeV/c. The dominance of the S-state is demonstrated by the 100% probability to find a neutron with spin parallel to the nuclear spin at low p_m. The presence of the small S'-state is demonstrated by the negative probability of $N^p(p_m)$ at low p_m. It is noted that $N^p(p_m)$ crosses zero at $p_m \approx 150$ MeV/c. The zero crossing is sensitive to the weighting of the 2-body and 3-body contributions to the proton asymmetry. The lack of agreement at high p_m is consistent with previous unpolarized measurements [17] and is likely due to breakdown of PWIA.

4. Summary

The spin dependent momentum distribution for the neutron and proton (in both 2-body and 3-body states) have been calculated from Faddeev solutions. We have demonstrated that sizable asymmetries arise for protons, even in the case of a pure S-state. Using measurements of spin-dependent quasielastic knockout and assuming the validity of PWIA, the spin asymmetries in the momentum distribution have been determined experimentally for the first time. Good agreement is observed between theory and experiment out to a missing momentum of 300 MeV/c. Our results indicate that there is a good theoretical understanding of the spin of ^{3}He at the nucleon level. This provides confidence that polarized ^{3}He can be used as an effective polarized neutron target for scattering experiments in nuclear and particle physics.

Study of the spin-dependent spectral function of ^{3}He should be pursued with weakly interacting electromagnetic probes out to high missing momentum and as a function of momentum transfer [18–20]. In particular, the use of the internal target technique offers the possibility to completely reconstruct the few-body final state. Future experiments should provide clean separation of the 2-body and 3-body contributions to the proton asymmetry and determine the contribution of the D-state at high nucleon momentum.

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