Measurement of double-polarization asymmetries in the quasi-elastic $^3\vec{\mathrm{He}}(\vec{\mathrm{e}}, \mathrm{e}'\mathrm{p})$ process

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We report on a precise measurement of double-polarization asymmetries in electron-induced breakup of ^{3}He proceeding to pd and ppn final states, performed in quasi-elastic kinematics at

$Q^2 = 0.25\,(\mathrm{GeV}/c)^2$ for missing momenta up to $250\,\mathrm{MeV}/c$. These observables represent highly sensitive tools to investigate the electromagnetic and spin structure of ^{3}He and the relative importance of two- and three-body effects involved in the breakup reaction dynamics. The measured asymmetries cannot be satisfactorily reproduced by state-of-the-art calculations of ^{3}He unless their three-body segment is adjusted, indicating that the spin-dependent final-state interaction in the breakup process is substantially smaller than previously thought.

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The ^{3}He nucleus represents a cornerstone of nuclear physics due to its potential to reveal the basic features of nuclear structure and dynamics in general. In particular, this paradigmatic three-body system offers an unique opportunity to study the interplay of two-nucleon and three-nucleon interactions, an effort at the forefront of nuclear physics research [1–3]. Modern theoretical descriptions of the structure and dynamics of ^{3}He require a detailed understanding of the nuclear ground-state wavefunction, the reaction mechanism including final-state interactions (FSI) and meson-exchange currents (MEC), as well as three-nucleon forces. The experiments on ^{3}He, particularly those involving polarization degrees of freedom, provide the essential input to these theories which need to be perpetually improved to match the current increase in experimental precision. The quality of this match is crucial to all ^{3}He-based experiments seeking to extract neutron information by utilizing ^{3}He as an effective neutron target, an approximation relying on a sufficient understanding of the proton and neutron polarization within polarized ^{3}He.

The ^{3}He nucleus is best studied by electron-induced knockout of protons, deuterons and neutrons, where the sensitivity to various aspects of the process can be greatly enhanced by the use of polarized beam and target. The focus of this paper is on the two-body (2bbu) and three-body (3bbu) breakup channels with proton detection in the final state, $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e'p})\mathrm{d}$ and $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e'p})\mathrm{pn}$, which were investigated concurrently with the already published $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e'd})$ data [4].

In a $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e'p})$ reaction the virtual photon emitted by the incoming electron transfers the energy ω and momentum $\boldsymbol{q}$ to the ^{3}He nucleus. The process observables are then analyzed in terms of missing momentum defined as the difference between the momentum transfer and the detected proton momentum, $\boldsymbol{p}_\mathrm{m} = |\boldsymbol{q} - \boldsymbol{p}_\mathrm{p}|$, thus $\boldsymbol{p}_\mathrm{m}$ corresponds to the momentum of the recoiled deuteron in 2bbu and the total momentum of the residual pn system in 3bbu.

The unpolarized $^3\mathrm{He}(\mathrm{e},\mathrm{e'p})$ process at low energies has been studied at MAMI, both on the quasi-elastic peak [5] and below it [6]. The bulk of our present high-energy information comes from the two experiments in quasi-elastic kinematics at Jefferson Lab [7, 8], resulting in reaction cross-sections at high p_m and yielding important insight into nucleon momentum distributions, isospin structure of the transition currents, FSI, and MEC. However, just as in the $(\mathrm{e},\mathrm{e'd})$ case, experiments that exploit polarization offer much greater sensitivity to the fine details of these ingredients. Such measurements have been extremely scarce. A single asymmetry data point with high uncertainty exists from NIKHEF [9, 10]. In addition, we have a precise measurement of both transverse and longitudinal asymmetries separately for the 2bbu and 3bbu channels in quasi-elastic kinematics [11, 12], but the measurement was restricted to (and summed over) relatively low p_m.

Early studies [13–15] have shown strong sensitivities of double-polarization asymmetries in ^{3}He breakup to the isospin structure of the electromagnetic current, to the sub-leading components of the ^{3}He ground-state wavefunction, as well as the tensor component of the nucleon-nucleon interaction. However, while in the deuteron channel these would manifest themselves at low p_m, the 2bbu and 3bbu proton channels should allow access to this information at high p_m, a region difficuly to explore experimentally. These diagrammatic evaluations ultimately gave way to more refined, full Faddeev calculations performed independently by the Bochum/Krakow [16, 17] and the Hannover/Lisbon [18–21] groups, which we use in this paper. The key feature of our experiment is the unmatched precision of the extracted asymmetries together with a broad kinematic range, with p_m extending to as far as $250\,\mathrm{MeV}/c$. This extended coverage represents a crucial advantage, since Faddeev calculations indicate that the manifestations of various wavefunction components, as well as the potential effects of three-nucleon forces, imply very different signatures as functions of p_m.

If both beam and target are polarized, the cross-section for the $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e'p})$ reaction has the form

$$\frac{\mathrm{d}\sigma(h,\vec{S})}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma_0}{\mathrm{d}\Omega}\left[1 + \vec{S}\cdot\vec{A}^0 + h(A_\mathrm{e} + \vec{S}\cdot\vec{A})\right] ,$$

where $\mathrm{d}\Omega = \mathrm{d}\Omega_\mathrm{e}\mathrm{d}E_\mathrm{e}\mathrm{d}\Omega_\mathrm{p}$ is the differential of the phase-space volume, σ_0 is the unpolarized cross section, $\vec{S}$ is the spin of the target, and h is the helicity of the electrons. The $\vec{A}^0$ and A_e are the asymmetries induced by the polarization of only the target or only the beam, respectively, while the spin-correlation parameter $\vec{A}$ is the asymmetry when both the beam and the target are polarized. If the target is polarized only in the horizontal plane defined by the beam and scattered electron momenta, the term $\vec{S}\cdot\vec{A}^0$ does not contribute [13], while A_e is suppressed and is negligible with respect to $\vec{A}$.

The orientation of the target polarization is defined by the angles θ^* and ϕ^* in the frame where the z-axis is along $\boldsymbol{q}$ and the y-axis is given by $\boldsymbol{p}_{\mathrm{e}} \times \boldsymbol{p}'_{\mathrm{e}}$. Any component of $\vec{A}$, i. e. the asymmetry at given θ^* and ϕ^* is then

$$A(\theta^*, \phi^*) = \frac{(\mathrm{d}\sigma/\mathrm{d}\Omega)_+ - (\mathrm{d}\sigma/\mathrm{d}\Omega)_-}{(\mathrm{d}\sigma/\mathrm{d}\Omega)_+ + (\mathrm{d}\sigma/\mathrm{d}\Omega)_-}\,, \qquad (1)$$

where the subscript signs represent the beam helicities. In this paper we report on the measurements of these asymmetries in $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})\mathrm{d}$ and $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})\mathrm{pn}$ processes. The measurements were performed during the E05-102 experiment at the Thomas Jefferson National Accelerator Facility in experimental Hall A [22], with the beam energy of 2.425 GeV in quasi-elastic kinematics at four-momentum transfer of $Q^2 = \boldsymbol{q}^2 - \omega^2 = 0.25\,(\mathrm{GeV}/c)^2$.

The beam was longitudinally polarized, with an average polarization of $P_{\mathrm{e}} = (84.3 \pm 2.0)\,\%$ measured by a Møller polarimeter. The target was a 40 cm-long glass cell containing the ^{3}He gas at approximately 9.3 bar ($0.043\,\mathrm{g/cm^2}$), polarized by hybrid spin-exchange optical pumping [23–26]. Two pairs of Helmholtz coils were used to maintain the in-plane target polarization direction at 67° and 156° with respect to $\boldsymbol{q}$, allowing us to measure $A(67^\circ, 0^\circ)$ and $A(156^\circ, 0^\circ)$, respectively. Electron paramagnetic and nuclear magnetic resonance [27–29] were used to monitor the target polarization, P_{t}, which was between 50 % and 60 %.

The scattered electrons were detected by a High-Resolution magnetic Spectrometer (HRS), while the protons were detected by the large-acceptance spectrometer BigBite equipped with a detector package optimized for hadron detection [30]. Details of the experimental setup and the procedure to extract the very pure sample of electron-proton coincidence events are given in Ref. [4].

The experimental asymmetry for each orientation of the target polarization was determined as the relative difference between the number of background-subtracted coincidence events corresponding to positive and negative beam helicities, $A_{\mathrm{exp}} = (N_+ - N_-)/(N_+ + N_-)$, where N_+ and N_- have been corrected for helicity-gated beam charge asymmetry, dead time and radiative effects. The corresponding physics asymmetries were calculated as $A = A_{\mathrm{exp}}/(P_{\mathrm{e}} P_{\mathrm{t}})$.

The resulting asymmetries as functions of p_{m} are shown in Fig. 1. The largest contribution to their systematic error comes from the relative uncertainty in the target polarization, P_{t}, which has been estimated at ±5 %, followed by the uncertainty in the target dilution factor (±2 %) and the absolute uncertainty of the beam polarization, P_{e} (±2 %). The uncertainty in the target orientation angle represents a minor contribution (±0.6 %) to the total uncertainty, totaling ≈ 6 % (relative).

Figure 1 also shows the results of the state-of-the-art three-body calculations of the Bochum/Krakow (B/K), Hannover/Lisbon (H/L) and Pisa (P) [31] groups. The

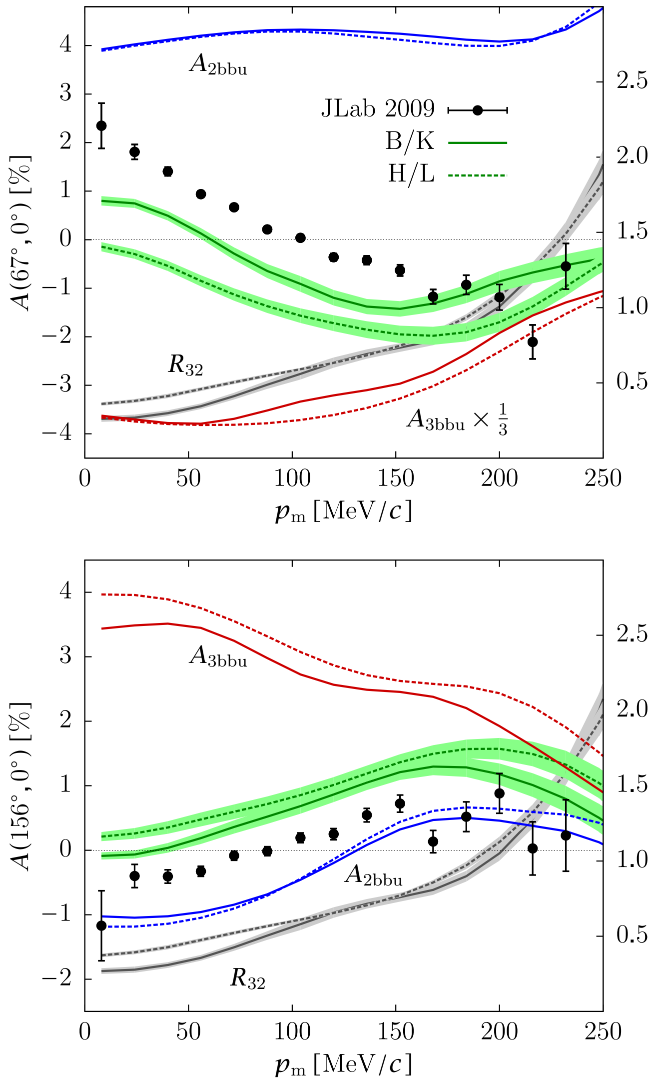

FIG. 1. (Color online.) The asymmetries $A(67^\circ, 0^\circ)$ (top) and $A(156^\circ, 0^\circ)$ (bottom) in the quasi-elastic $^3\vec{\mathrm{He}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$ process (2bbu and 3bbu combined) as functions of missing momentum, compared to theoretical predictions (green) showing the 2bbu (blue) and 3bbu (red) contributions as well as the ratio of 3bbu and 2bbu cross-sections (grey). All full (dashed) lines correspond to B/K (H/L) calculations, respectively.

B/K calculations are based on the AV18 nucleon-nucleon potential [32, 33] and involve a complete treatment of FSI and MEC, but do not include three-nucleon forces; the Coulomb interaction is taken into account in the ^{3}He bound state. The H/L calculations are based on the coupled-channel extension of the charge-dependent Bonn potential [34] and also include FSI and MEC, while the Δ isobar is added as an active degree of freedom providing a mechanism for an effective three-nucleon force and for exchange currents. Point Coulomb interaction is added in the partial waves involving two charged baryons. The Pisa calculations are based on the AV18 interaction model (augmented by the Urbana IX three-nucleon force [35]), in which full inclusion of FSI is taken into account by means of the variational pair-correlated hyperspherical harmonic expansion, as well as MEC. Coulomb interaction is included in full (not only in the ^{3}He ground state). In contrast to the B/K and H/L approaches, the Pisa calculations are not genuine Faddeev calculations but are of equivalent precision and are expected to account for all relevant reaction mechanisms. At present, the Pisa group only provides 2bbu calculations. Due to the extended experimental acceptance, all theoretical asymmetries were appropriately averaged. Details can be found in [4].

Neither the B/K nor the H/L calculation reproduces the measured asymmetries to a satisfactory level. Similarly to our findings in the deuteron channel, the theories approximately capture their overall functional forms, but exhibit systematic vertical offsets of up to two percent. In calculations a strong cancellation is involved in obtaining each total asymmetry from its 2bbu and 3bbu contributions, which are typically opposite in sign and of very different magnitudes. Nevertheless, the failure of the theories to reproduce the data can be traced to the 3bbu asymmetry alone, as discussed in the following.

Since the energy resolution of our measurement was insufficient to directly disentangle the 2bbu and 3bbu channels, the individual asymmetries were extracted by restricting the data sample to $p_{\mathrm{m}} \approx 0$ and studying the dependence of $A(67^\circ, 0^\circ)$ and $A(156^\circ, 0^\circ)$ in terms of the cut in missing energy, $E_{\mathrm{m}} = \omega - T_{\mathrm{p}} - 7.7\,\mathrm{MeV}$. The comparison of the measured E_{m} spectrum with the simulated one revealed that in spite of the overlap between the two channels, the lowest portion of the distribution at $E_{\mathrm{m}} < 0$ is dominated by 2bbu, thus allowing for the extraction of the corresponding asymmetry, A_{2bbu}, which agrees with the calculations to better than 0.5 % (absolute): see Fig. 2 (left). In this region the contribution of 3bbu to the experimental cross-section is approximately 7 %, suggesting that near the threshold the size of the 3bbu asymmetry is about 1 % smaller than the prediction. However, a better insight into the 3bbu asymmetry has been obtained by investigating the data at $E_{\mathrm{m}} > 0$. Considering that the measured asymmetries contain also the 2bbu contribution, the 3bbu asymmetry (Fig. 2 (right)) has been extracted from the data as

$$A_{\mathrm{3bbu}} = \frac{(1 + R'_{32})A_{\mathrm{exp}} - A_{\mathrm{2bbu}}}{R'_{32}}\,,$$

where R'_{32} is the 3bbu/2bbu cross-section ratio shown in Fig. 1 corrected for finite-resolution and radiative effects. Typically R'_{32} ranges from 0.20 to 0.33 and is assumed to be well under control in both B/K and H/L calculations. The extracted asymmetries are in good agreement with the theory in the limit where the whole spectrum ($E_{\mathrm{m}} \leq 50\,\mathrm{MeV}$) is considered in the analysis, but strongly deviaties from the theory at the threshold ($E_{\mathrm{m}} \leq 2.5\,\mathrm{MeV}$) for the 3bbu reaction channel.

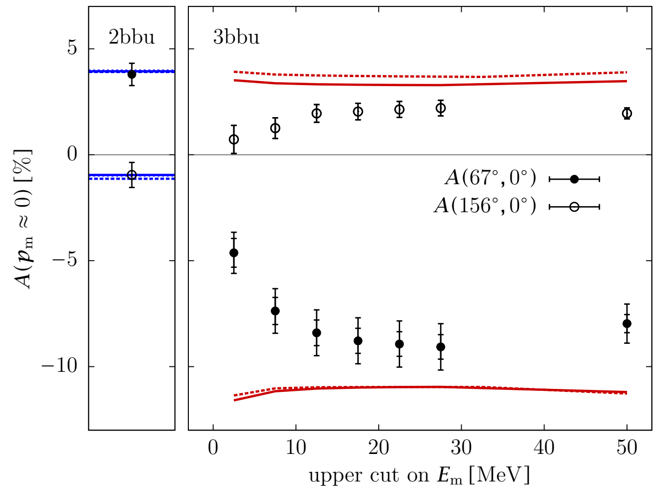

FIG. 2. (Color online.) The extracted asymmetries for 2bbu (left) and 3bbu (right). Curve notation as in Fig. 1, with the addition of the Pisa 2bbu calculation in the left panel (blue dotted lines hidden beneath the full and dashed lines).

In an effort to compensate for the effect of spin orientation of protons inside the polarized ^{3}He nucleus, we have divided the nuclear asymmetries by the asymmetries for elastic $\vec{\mathrm{e}}$-$\vec{\mathrm{p}}$ scattering at the same value of four-momentum transfer; see Fig. 3. In a simplified picture of the $^3\vec{\mathrm{He}}(\vec{\mathrm{e}}, \mathrm{e'p})$ process, one would expect the 2bbu ratio at $p_{\mathrm{m}} \approx 0$ to be $-1/3$, corresponding to the effective polarization of the (almost free) proton inside the polarized ^{3}He nucleus, while the 3bbu ratio should vanish because any of the two oppositely polarized protons could be knocked out in the process. Indeed, in the 2bbu case both the experimental and the predicted ratios coincide almost perfectly, at the anticipated "naive" value of $-1/3$. On the other hand, in the 3bbu case the predictions cluster approximately around unity (and apparently retain a residual dependence on θ^*), while the two experimental ratios are much smaller (and mutually consistent).

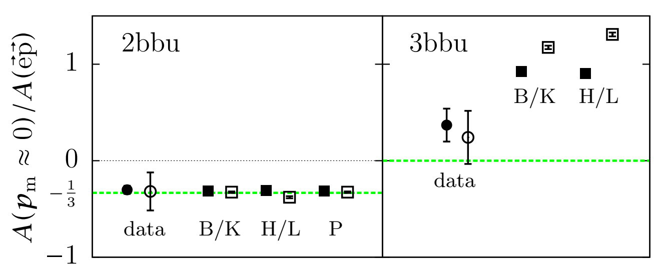

FIG. 3. (Color online.) The $A(67^\circ, 0^\circ)$ (full symbols) and $A(156^\circ, 0^\circ)$ (empty symbols) asymmetries for 2bbu (left) and 3bbu (right) divided by the corresponding asymmetries for elastic $\vec{\mathrm{e}}$-$\vec{\mathrm{p}}$ scattering at the same value of Q^2. In both panels the data (circles) are compared to the calculations (squares).

In conclusion, we have provided the world-first, high-precision measurement of double-polarization asymmetries for proton knockout from polarized ^{3}He nuclei at two different spin settings and over a broad range of momenta. Two state-of-the-art theoretical approaches to the ^{3}He system are able to approximately accommodate the main kinematical and structural features of our data set. Since the asymmetries are rather small and strong cancellations of the two-body and three-body breakup contributions are involved, the agreement can be deemed satisfactory and the theoretical framework justified. However, the large precision of our measurements has been able to reveal a substantial deficiency in the calculations, pointing to an incomplete understanding of the spin-dependent final-state interaction in the three-body breakup.

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