Transverse-Longitudinal Asymmetry in the Quasielastic $^3\overrightarrow{\text{He}}(\vec{e}, e')$ Reaction

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The transverse-longitudinal asymmetry $A_{TL'}$ in $^3\overrightarrow{\text{He}}(\vec{e}, e')$ quasielastic scattering at momentum transfer $Q^2 = 0.14(\text{GeV}/c)^2$ has been measured to be $1.52 \pm 0.55(\text{stat}) \pm 0.15(\text{syst})\%$. The plane wave impulse approximation (PWIA) prediction for this measurement ranges from 2.1% to 2.9%, where the variation is due to uncertainty in the initial state wave function, nucleon form factors, and off-shell prescription. The data may suggest a suppression with respect to the PWIA, which has also been observed for the unpolarized longitudinal response function.

The three-body system has played a significant role as a testing ground between theory and experiment in nuclear physics. The ^{3}H and ^{3}He nuclei are unique in that, although they are relatively tightly bound, essentially exact nonrelativistic Faddeev solutions for the ground state (g.s.) have been obtained using a variety of two-nucleon (NN) potentials. Measurement of inclusive unpolarized quasielastic (QE) electron scattering (where only the scattered electron is detected) from these nuclei at intermediate energies has provided important information on the g.s. structure and on the nature of the reaction mechanism. In particular, the unpolarized cross section has been separated in terms of the transverse and longitudinal response functions, R_T and R_L, respectively [1,2]. The experimentally determined R_T is well described by the plane wave impulse approximation (PWIA), which ignores effects of final state interactions (FSI) and meson-exchange currents (MEC). However, the measured R_L is suppressed with respect to PWIA at the QE peak at low Q^2. Recently, treatments of the trinucleon continuum which include FSI [3,4] and a calculation which employs a path integral technique [5] have brought theory in better agreement with the R_L data at low momentum transfers.

Measurement of spin observables allows one to study additional quantities which are inaccessible or difficult to measure in unpolarized scattering experiments. Inclusive electron scattering from the spin-$\frac{1}{2}$ ^{3}He target is a particularly simple case [6]: For both beam and target polarized, the spin-dependent contribution to the cross section is completely contained in two additional response functions, a transverse response $R_{T'}$, and an interference between longitudinal and transverse multipoles $R_{TL'}$, beyond the spin-independent R_L and R_T. An experimentally clean signature of these new responses is the spin-dependent asymmetry, defined as

$$A = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \quad (1)$$

where the subscript $+$ $(-)$ refers to the helicity of the incident electrons, and σ is the differential cross section. In terms of the $R_K(Q^2, \omega)$, A can be written [6]

$$A = -\frac{\cos\theta^* v_{T'}R_{T'} + 2\sin\theta^*\cos\phi^* v_{TL'}R_{TL'}}{v_T R_T + v_L R_L}, \quad (2)$$

where θ^* and ϕ^* are the polar and azimuthal angles defining the direction of the target spin with respect to the momentum transfer $\vec{q}$, the v_K are kinematic factors, ω is the electron energy loss, and $Q^2 \equiv |\vec{q}|^2 - \omega^2$. Hence, orienting the target spin at $\theta^* = 90°$ $(0°)$ selects the asymmetry piece $A_{TL'}$ $(A_{T'})$ proportional to $R_{TL'}$ $(R_{T'})$.

Faddeev calculations [7,8] predict that the ^{3}He g.s. is predominantly in a spatially symmetric S state ($\sim$90% of the spin-averaged wave function), where the two protons are in a spin singlet state so that the nuclear spin is entirely due to the neutron. A net proton polarization is carried by the remaining "small" components, notably the D state ($\sim$8%), where the three nucleon spins are oriented (roughly) opposite to the nuclear spin, and the mixed-symmetry S' state ($\sim$1%). Recent measurements of spin-dependent proton-induced nucleon knockout from polarized ^{3}He ($^3\overrightarrow{\text{He}}$) support these results [9].

As a consequence of the S-state dominance, spin observables in scattering from $^3\overrightarrow{\text{He}}$ are in general expected to be sensitive to neutron properties. A number of experiments have been carried out or proposed to measure the neutron electromagnetic (electric G_E^n and magnetic G_M^n) form factors in QE electron scattering [10–13] and the neutron spin structure functions in deep-inelastic electron scattering from $^3\overrightarrow{\text{He}}$ [14]. A basic premise in the extraction of neutron form factors from spin-dependent electron-^{3}He scattering is that both the nuclear ground state spin structure and the QE scattering mechanism are well understood.

To date, theoretical studies of QE inclusive scattering from $^3\overrightarrow{\text{He}}$ have employed the PWIA for the scattering mechanism, in which the ^{3}He $R_{TL'}$ ($R_{T'}$) response contains a contribution proportional to $G_M^n G_E^n$ (G_M^{n2}). Blankleider and Woloshyn, using closure to sum over final states [15], originally predicted that $A_{TL'}$ would be strongly sensitive to G_E^n, at the kinematics of the experiment reported here. This was confirmed by Ciofi degli Atti, Pace, and Salmè [16], who studied the effect of nuclear binding using a full spin-dependent spectral function to describe the $^3\overrightarrow{\text{He}}$ g.s. However, a more sophisticated analysis, which was recently performed [7], points out an inconsistency in the previous predictions for $A_{TL'}$ (while it agrees with those for $A_{T'}$). In particular, it shows, at the kinematics of the measurement reported here, a dominant proton contribution to $A_{TL'}$, which greatly reduces the sensitivity to G_E^n.

As previously reported [13], we have measured $A_{T'}$ under similar kinematic conditions to the experiment described here. The data are in good agreement with PWIA calculations, allowing the extraction of a value for G_M^{n2}. While $A_{T'}$ is dominated by the effects of the S-state neutron, the asymmetry $A_{TL'}$ in PWIA at these kinematics arises from the sum of a contribution due to the S'- and D-state protons ($\sim$75%) and a neutron contribution proportional to G_E^n ($\sim$25%). Thus, $A_{TL'}$ is not only significantly smaller (and correspondingly more difficult to measure) than $A_{T'}$, but also provides substantially new information which can be used to constrain our understanding of electron scattering at intermediate energies from the three-body system.

The purpose of the present Letter is twofold: First, we report a measurement of $A_{TL'}$ at $Q^2 = 0.14$ $(\text{GeV}/c)^2$

which has significantly higher precision than two previous experiments done at similar Q^2 [10,11]. Second, we present a theoretical study of the $A_{TL'}$ asymmetry in PWIA using the formalism of Refs. [7,17] and compare its results with the data.

The experiment was carried out at the MIT-Bates Linear Accelerator Center using a 370 MeV longitudinally polarized, pulsed electron beam and a polarized ^{3}He gas target. Details about the beam and target can be found in an earlier publication [13]; the average beam and target polarizations were (36.5 ± 1.5)% and (38 ± 1.1)%, respectively. To maximize sensitivity to $A_{TL'}$, the target spin was oriented at 42.5° with respect to the beam direction. A total beam charge of 5020 μA h was accumulated. The scattered electrons were detected in the OHIPS spectrometer using a detector package consisting of two crossed drift chambers, three planes of plastic scintillators, and an isobutane gas Čerenkov detector. The trigger was formed by a coincidence of the three scintillators. Pion background was rejected in software using the Čerenkov information. The spectrometer was positioned at a scattering angle of 70.1° and had a central momentum of 285 MeV/c, corresponding to QE kinematics. The momentum resolution was $\leq$1.2% FWHM over the momentum acceptance of 9.5%. The target length viewed by the spectrometer was collimated with slits to 10 cm along the beam. The solid angle acceptance was 12 msr as determined by ^{12}C(e, e). Background scattering of beam halo from the copper target walls was measured at regular intervals with the target cell empty and was approximately 5% of the full target yield. As a check on the experimental procedure, elastic data were taken at regular intervals with OHIPS. The resulting elastic asymmetry of (29.9 ± 3.9)% agrees well with the prediction of 32.1% calculated from elastic form factor data [18].

$A_{TL'}$ was extracted from the detected spin-dependent yield according to Eq. (1) as a function of the electron energy loss ω. To account for the dilution from unpolarized scattering, the result was divided by the product of the beam and target polarizations. Corrections were applied for target-related background ($+5$%) and radiative effects (-15%). The contribution to the asymmetry of helicity-correlated background and efficiency variations was negligible. The measured asymmetry is shown in Fig. 1. (The curves in the figure are discussed below.) Combining all the data over the experimental energy acceptance ($72 \leq \omega \leq 99$ MeV) yields a value of $A_{TL'} = (1.52 \pm 0.55 \pm 0.15)$%, as detailed in Table I.

To interpret the data, the main PWIA model dependences were identified and quantified. Figure 2(a) presents the predicted variation in $A_{TL'}$ for three realistic form factor models [using the Paris force [19] and CC1$^{(0)}$ single-nucleon off-shell (o.s.) prescription [17]]: Galster [20] (the solid base-line curve), Gari-Krümpelmann [21] (dashed curve), and Höhler [22] (dot-dashed curve).
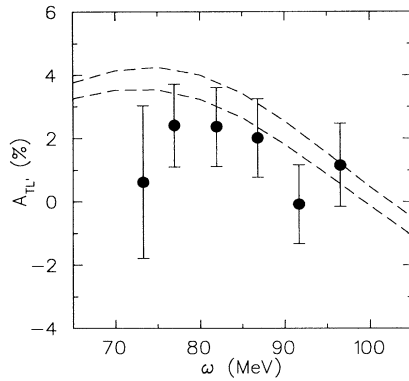
FIG. 1. The transverse-longitudinal asymmetry $A_{TL'}$ as a function of electron energy transfer ω. The errors on the data are statistical only. The curves represent the upper and lower bounds of our PWIA calculation (see text).

(Note, however, that Gari-Krümpelmann at high Q^2 has been found to be inconsistent with data [23].)

Similarly, Fig. 2(b) shows the $A_{TL'}$ variation with NN potential (for Galster form factors and CC1$^{(0)}$ o.s. prescription); 18-channel momentum space Faddeev equations [8] were used to generate ^{3}He g.s. wave functions for the Paris (the solid base-line curve), Reid soft-core [24] (dashed curve), and Bonn B [25] (dot-dashed curve) potentials. Of the currently available potential models, these three models yield a representative spread for the fraction of S' and D state in the g.s. (see Table II). (An additional calculation, in which individual partial waves are varied, demonstrates that $A_{TL'}$ increases with the amount of either the S' or the D state.)

Finally, Fig. 2(c) compares the effect on $A_{TL'}$ of different o.s. current prescriptions (for Galster form factors
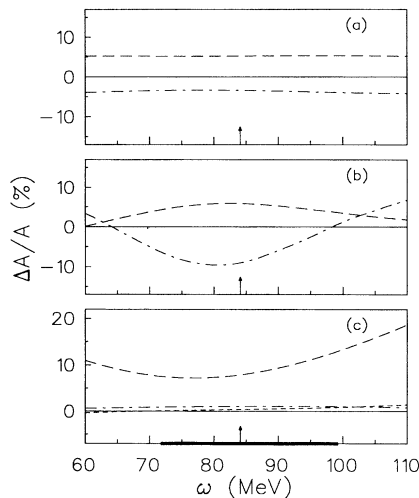

FIG. 2. Variation $\Delta A/A \equiv (A - A_{\text{base line}})/\overline{A}_{\text{base line}}$ of $A_{TL'}$ with different (a) form factor parametrizations, (b) NN potential models, and (c) single-nucleon o.s. prescriptions (see text). The arrow indicates the location of the QE peak. The experimental acceptance is shown as a horizontal band.

TABLE I. Results of the asymmetry measurement averaged over the experimental energy acceptance ($72 \leq \omega \leq 99$ MeV). The uncertainties are statistical and systematic, respectively. The second row corresponds to data taken with reversed target spin; hence the negative sign.

Charge (μA h)	θ^*	ϕ^*	A (%)
2878	87°	0°	1.65 ± 0.72
2142	93°	180°	-1.33 ± 0.86
5020 (combined)			$1.52 \pm 0.55 \pm 0.15$
Theory	87°	0°	$2.1 - 2.9$

and the Paris force), though only that of Ciofi degli Atti, Pace, and Salmè [16,26] (the dashed curve) differs appreciably from the others: CC1$^{(0)}$ (the solid base-line curve), CC2$^{(0)}$ [17] (short-dashed curve), and Schulze and Sauer [7] (dot-dashed curve). It must be noted, however, that our o.s. comparison omits many other, equally acceptable prescriptions (such as non-current-conserving forms; for detailed discussion see Ref. [17]), and so yields only a *minimum* uncertainty.

Summarizing the results of Fig. 2, the theoretical $A_{TL'}$ sensitivity (averaged over our experimental ω acceptance) is $\pm 4.5\%$ $\overline{\Delta A/A}$ for varying nucleon form factor parametrizations, $\pm 6\%$ $\overline{\Delta A/A}$ for NN potential models, and $\pm 4.5\%$ $\overline{\Delta A/A}$ for o.s. current prescriptions. The stability of ΔA with choice of base-line calculations in each case indicates that these uncertainties are roughly independent and so add linearly. The average of the base line calculation is $\overline{A}_{\text{base line}} = 2.52\%$.

This total model uncertainty is responsible for the spread of PWIA predictions shown with the data in Fig. 1 (dashed curves). The lower bound for $A_{TL'}(\omega)$ results from Höhler form factors [22] with the Bonn B potential [25] and CC1$^{(0)}$ o.s. prescription [17]. The upper bound is obtained using the Gari-Krümpelmann form factors [21] with the Reid soft-core potential [24], and o.s. prescription of Ciofi degli Atti, Pace, and Salmè [16,26]. When averaged over the experimental acceptances (weighting with the experimental error), the PWIA yields minimum and maximum values of $(2.15 \pm 0.05)\%$ and $(2.85 \pm 0.05)\%$ (where the error stems from a Monte Carlo correction for the finite angular acceptance). Hence, for our experimental conditions the average $A_{TL'}$ predicted by PWIA models varies between 2.1% and 2.9%.

Although the ω dependence of the data seems to be well described by PWIA (Fig. 1), the average of the data (Ta-

TABLE II. Main properties of the three-body wave functions used in the calculation.

NN potential	$P(S)$ (%)	$P(S')$ (%)	$P(D)$ (%)	$E_B(^3\text{H})$ (MeV)
Reid soft-core	89.34	1.45	9.21	-7.23
Paris	90.36	1.38	8.25	-7.39
Bonn B	91.75	1.18	7.07	-8.10

ble I) is low at the level of $\sim(1-2.5)\sigma$. Such a discrepancy may indicate the presence of FSI and MEC, as suggested by the recent calculations to explain R_L suppression in inclusive reactions [3–5] and by calculations for spin-dependent coincidence reactions [27].

In addition, the PWIA results demonstrate that the sensitivity of $A_{TL'}$ to G_E^n at this Q^2 is largely masked by the residual model dependence—at best G_E^n can be determined with a theoretical uncertainty comparable to that obtained with existing data on elastic electron-deuteron scattering [28]. However, we point out that the PWIA model predicts that the ability to extract information on G_E^n from inclusive spin-dependent scattering from $^3\overrightarrow{\mathrm{He}}$ greatly improves at higher Q^2 [~ 0.6 (GeV/$c)^2$], where the ratio of G_E^n to the proton form factors is expected to increase significantly.

In summary, we have measured the $A_{TL'}$ asymmetry in $^3\overrightarrow{\mathrm{He}}(\vec{e}, e')$ QE scattering at $Q^2 = 0.14$ (GeV/$c)^2$. The uncertainties in the theoretical PWIA model for this reaction have been studied in detail for the first time. The PWIA study has shown that the large spread in $A_{TL'}$ predictions at this Q^2 represents a presently inescapable model uncertainty, in which the sensitivities to G_E^n, small components of the wave function, and o.s. prescription are comparable. The data are low compared to the PWIA predictions at the $(1-2.5)\sigma$ level, which may be an indication of FSI or MEC effects. It would be of great interest to extend the calculational frameworks [3–5] which appear to give a reasonable description of the unpolarized longitudinal response, to include polarization degrees of freedom. Calculations which include FSI and MEC effects are desirable to extract information on G_E^n from $A_{TL'}$ measurements using inclusive scattering from polarized ^{3}He at higher Q^2, where PWIA model uncertainties are predicted to be significantly smaller.

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