Polarization Transfer in the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ Reaction at $Q^2 = 0.8$ and 1.3 $(\mathrm{GeV}/c)^2$

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Proton recoil polarization was measured in the quasielastic $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ reaction at $Q^2 = 0.8$ and 1.3 $(\mathrm{GeV}/c)^2$ with unprecedented precision. The polarization-transfer coefficients are found to differ from those of the $^1\mathrm{H}(\vec{e}, e'\vec{p})$ reaction, contradicting a relativistic distorted-wave approximation and favoring either the inclusion of medium-modified proton form factors predicted by the quark-meson coupling model or a spin-dependent charge-exchange final-state interaction. For the first time, the polarization-transfer ratio is studied as a function of the virtuality of the proton.

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Electron-nucleon scattering is a powerful tool for probing the structure of nucleons. For over a decade, access to high-quality polarized electron beams has allowed the nucleon's electromagnetic properties to be explored through measurement of polarization observables. In elastic electron-nucleon scattering, the polarization-transfer technique allows measurement of the Sachs form-factor ratio G_E/G_M that is directly proportional to the ratio of transverse and longitudinal polarization observables P'_x/P'_z in the single-photon exchange approximation [1,2]. This technique [3] benefits from a large cancellation of systematic uncertainties, unlike the Rosenbluth separation technique, which relies on repeated cross-section measurements. Several recent experiments have extracted G_E/G_M of the proton by using this method [4–7].

The question of if and how the nucleon structure is modified within the nuclear medium has been hotly debated since the discovery of the nuclear EMC effect, which showed that quark momentum distributions within nuclei differ from those within free nucleons. Indeed, a deviation of G_E and G_M of a nucleon immersed in a nuclear medium from their free-space values is predicted by Lu *et al.* [8,9] by using the quark-meson coupling (QMC) model. These results are consistent with experimental constraints from the Coulomb sum rule; see [10,11]. In addition to the QMC model, many other model calculations predict the in-medium modification of nucleon structure; for recent examples, see [12–15]. Ciofi degli Atti *et al.* predict that the proton form factors are strongly correlated with the excitation of the residual system and the virtuality of the ejected proton [16].

The polarization-transfer technique can be used to help settle this question by using quasielastic nucleon knockout. In that case, the ratio G_E/G_M remains approximately proportional to P'_x/P'_z, allowing modifications of the form factors to be determined. However, in-medium nucleon interactions complicate this picture and even raise the question as to whether the concept of medium modifications is a meaningful one, due to the complex nature of the in-medium interaction. Predictions from Schiavilla *et al.* [17] contend that final-state interactions (FSIs) including charge-exchange processes and meson-exchange currents lead to a quenching of 10% in the polarization-transfer ratio P'_x/P'_z in the quasielastic scattering reaction $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ compared with the free-space reaction $^1\mathrm{H}(\vec{e}, e'\vec{p})$. The correct treatment of FSIs in a model calculation is essential to separate any unconventional medium effects from FSIs, since both influence the polarization-transfer observables. To help settle this debate, precision measurements are needed with the polarization-transfer coefficients P'_x/P'_z mapped in detail in a region of low (<100 MeV$/c$) missing momentum, where such FSI complications are minimized, and as a function of the virtuality of the ejected proton. Dependence on the latter is a simple and straightforward corollary of models with medium modifications.

This Letter reports on measurements of the polarization-transfer coefficients P'_x and P'_z in the quasielastic $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ reaction performed at Jefferson Lab in Hall A: experiment E03-104. Data were taken at four-momentum transfers of $Q^2 = 0.8$ and 1.3 $(\mathrm{GeV}/c)^2$ within a missing-momentum range <160 MeV$/c$. The ^{4}He target was chosen for its high nuclear density and relative theoretical modeling simplicity. A recent study of the EMC effect [18] has shown that the effect on nucleons in ^{4}He is comparable to the effect on nucleons in ^{12}C. The low missing-momentum regime was chosen to reduce the contribution from many-body effects, although a weaker contribution from in-medium modification effects is expected. Additional $^1\mathrm{H}(\vec{e}, e'\vec{p})$ scattering data also were taken to provide unmodified proton scattering measurements as a basis for comparison. The carbon analyzing power of the polarimeter was also extracted from the $^1\mathrm{H}(\vec{e}, e'\vec{p})$ data.

Kinematic settings for the present experiment are given in Table I. For both $^1\mathrm{H}(\vec{e}, e'\vec{p})$ and $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$, the scattered electron and ejected proton were detected in coincidence in two high-resolution spectrometer arms. For the nine ^{1}H settings, the central momenta for the proton were adjusted in 2% increments from -8% to $+8\%$ in order to produce similar coverage of the focal plane, as in $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ scattering. This allows for detailed studies of the spin transport and other instrumental effects. Beam currents up to 80 μA and beam polarizations of 85% were used. The proton spectrometer was equipped with a focal plane polarimeter, which measures the asymmetry of polarized protons scattered from a carbon analyzer [4]. The spin precession of the proton in the magnetic field of the spectrometer was calculated by using the COSY software [19]. A maximum likelihood method was then employed in conjunction with the beam helicity, the carbon analyzing power, and the proton spin precession to extract the polarization of the ejected proton at the target [20]. The large amount of statistics accumulated in this experiment has allowed the extraction of $\mu G_E/G_M$ from the data with strict missing-energy and missing-momentum cuts to prevent any effects from diluting the polarization observables. For $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ scattering, tight cuts on the reconstructed missing mass spectrum were used to ensure that quasielastic knockout of the proton leaves the undetected ^{3}H intact. Radiative effects due to single-photon emission [21], as well as radiative corrections from two-photon exchange to the polarization ratio P'_x/P'_z [22], are predicted to be less than 0.5%. Radiative effects on the ratio were minimized with missing-energy and missing-momentum cuts, but no specific radiation corrections were applied to the data.

Figure 1 shows our results for the polarization-transfer coefficients as a function of the missing momentum. Here,

TABLE I. Table of kinematic settings for experiment E03-104. Here E_0 is the incident beam energy, p_p is the central momentum setting of the proton spectrometer, θ_p is the central angle setting for the proton spectrometer, p_e is the central momentum setting of the electron spectrometer, and θ_e is the central angle setting for the electron spectrometer.

Kinematic setting	Q^2 $(\mathrm{GeV}/c)^2$	E_0 (GeV)	Target	p_p (GeV/c)	θ_p (deg)	p_e (GeV/c)	θ_e (deg)
A1–9	0.8	1.987	^{1}H	0.991 ± 8%	50.668	1.561	-29.440
A10	0.8	1.987	^{4}He	1.004	49.115	1.532	-29.730
B1–9	1.3	2.637	^{1}H	1.334 ± 8%	45.289	1.944	-29.221
B10	1.3	2.637	^{4}He	1.353	43.920	1.909	-29.462

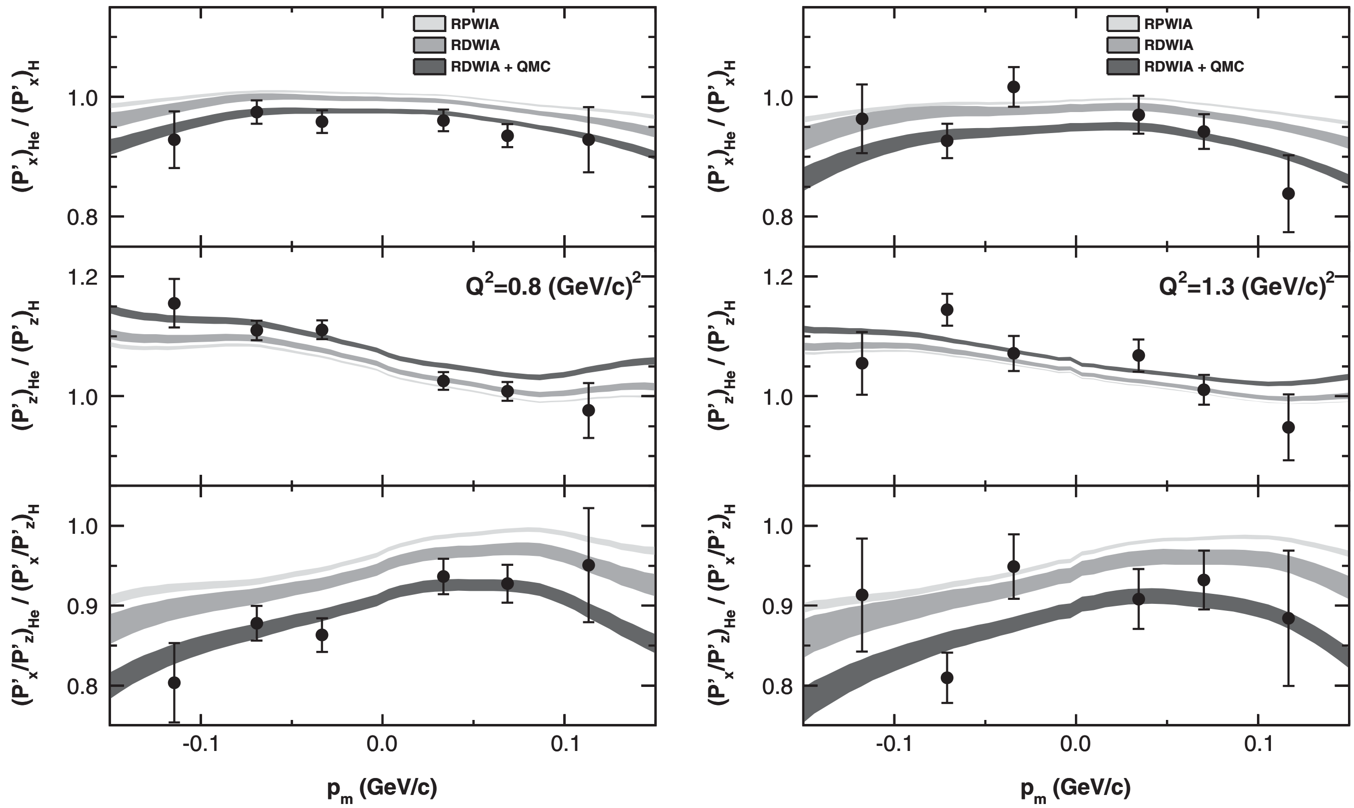

FIG. 1. The individual polarization-transfer coefficients from ^{4}He normalized to ^{1}H, $(P'_x)_{\mathrm{He}}/(P'_x)_{\mathrm{H}}$, and $(P'_z)_{\mathrm{He}}/(P'_z)_{\mathrm{H}}$, and the double ratio R versus the missing momentum p_m for $Q^2 = 0.8$ (GeV$/c)^2$ (left) and $Q^2 = 1.3$ (GeV$/c)^2$ (right). The bands represent RPWIA (light gray), RDWIA calculations (medium gray), and RDWIA + QMC calculations (dark gray) [25]. See the text for a description of the models.

the sign of the missing momentum is positive if the component of the missing-momentum vector along the momentum-transfer direction is positive. The individual polarization-transfer coefficients from the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ normalized to the $^1\mathrm{H}(\vec{e}, e'\vec{p})$ reaction, $(P'_x)_{\mathrm{He}}/(P'_x)_{\mathrm{H}}$ and $(P'_z)_{\mathrm{He}}/(P'_z)_{\mathrm{H}}$, and the double ratio R are shown along with acceptance-corrected calculations from the Madrid group [23,24]. Here, R is defined as

$$R = \frac{(P'_x/P'_z)_{^4\mathrm{He}}}{(P'_x/P'_z)_{^1\mathrm{H}}}. \tag{1}$$

The Madrid group calculations use a relativistic wave function for the bound state that reproduces the exclusive $^4\mathrm{He}(e, e'p)$ cross-section data [25]. The calculations are represented through bands whose variation in width depends on the nuclear current operators $cc1$ and $cc2$ [26] and the optical potential models, McNeil-Ray-Wallace (MRW) [27] and relativistic Love-Franey [28], used. The light, medium, and dark gray bands represent calculations from a relativistic plane-wave impulse approximation (RPWIA), relativistic distorted-wave impulse approximation (RDWIA), and a RDWIA that includes an in-medium-modified form factor as predicted by Lu *et al.* with the QMC model [8], respectively. At both $Q^2 = 0.8$ and 1.3 (GeV$/c)^2$, the RPWIA and RDWIA calculations overestimate the data significantly. With RDWIA + QMC, the calculation is in better agreement with the data. Uncertainties from model wave functions, current operators, or choice of MRW or relativistic Love-Franey optical potentials are small, which allows discrimination between the data and the conventional RDWIA calculations. The RDWIA calculations with medium-modified nucleon form factors predict a greater divergence from standard RDWIA calculations at missing momenta further from zero.

The expected effect on the hydrogen-normalized polarization coefficients from in-medium-modified form factors can be estimated by comparing the $\vec{e}p$ elastic scattering to the quasielastic case. In elastic scattering, the polarization coefficients themselves can be expressed directly as functions of P'_x/P'_z. One would expect a decrease for $(P'_x)_{\mathrm{He}}/(P'_x)_{\mathrm{H}}$ and an increase for $(P'_z)_{\mathrm{He}}/(P'_z)_{\mathrm{H}}$, consistent with the overall observed quenching of R, which is indeed consistent with our data for both observables. These results are also in agreement with the full model, RDWIA + QMC.

In Fig. 2, results are shown as the polarization-transfer double ratio R plotted versus Q^2. The results agree with previous results [29] from Mainz [30] and JLab experiment

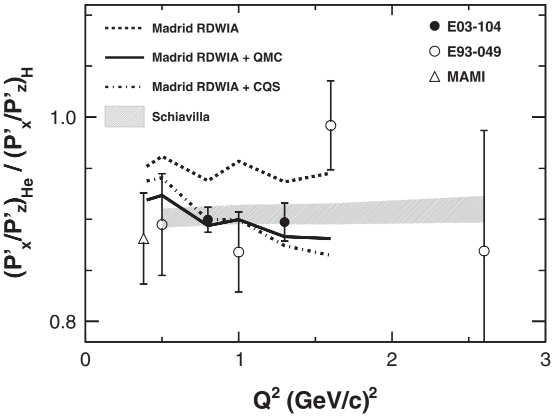

FIG. 2. Experimental results for R versus Q^2 for E03-104 (black circles), E93-049 (open circles) [31], and MAMI (open triangle) [30]. The curves represent RDWIA (dashed), RDWIA + QMC (solid), and RDWIA + CQS (dash-dotted) calculations with the current operator $cc2$ and the MRW optical potential [25]. The gray band represents Schiavilla's model [17]; see text for details.

E93-049 [31] establishing the quenching of R and its Q^2 dependence with previously unattained confidence; additionally, the calculated $\mu G_E/G_M$ values for ${}^1\mathrm{H}(\vec{e}, e'\vec{p})$ are in good agreement with world data [4–7]. The experimental results for R and $\mu G_E/G_M$ are also listed in Table II. With data for ${}^1\mathrm{H}(\vec{e}, e'\vec{p})$ and ${}^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ obtained under near-identical experimental conditions, calculating the double ratio R results in a significant cancellation of systematic uncertainties.

The theoretical calculations shown in Fig. 2 include a RDWIA calculation with free-space proton form factors (dashed line) and RDWIA calculations that include an in-medium-modified form factor as predicted by Lu *et al.* with the QMC model [8] (solid line) and an in-medium-modified form factor as predicted in the chiral quark soliton model by Smith and Miller [14] (dash-dotted line). Theoretical calculations from Schiavilla [17] are included in Fig. 2 as a gray band and assume a missing momentum close to zero and have not been acceptance corrected. Schiavilla shows with conventional many-body calculations that a model with free-space nucleon form factors can describe R as a function of Q^2. The difference in modeling the FSIs accounts for most of the discrepancy between Schiavilla's and the Madrid group's calculations. Schiavilla's calculation includes meson-exchange current effects paired with tensor correlations that suppress R by 4% and include both a spin-dependent and a spin-independent charge-exchange term in the final-state interaction that suppress R by an additional 6%, all of which are not included in the Madrid group's calculations. The spin-orbit terms in Schiavilla's FSI calculations are not well constrained, and the Monte Carlo technique employed in the model calculation introduces a statistical uncertainty represented in the width of the gray band in Fig. 2.

Figure 3 shows R as a function of the proton virtuality $v = p^2 - m_p^2$. Here, p is the proton four-momentum in the ${}^4\mathrm{He}$ nucleus and is defined as $p^2 = (m_{\mathrm{He}} - E_t)^2 - p_t^2$ in the impulse approximation, where E_t and p_t are, respectively, the energy and momentum of the undetected triton. The dashed line is a linear fit to the data assuming $R = 1$ at $v = 0$ and is included as a simple approximation of the expected trend in virtuality. The RDWIA models including medium-modified proton form factors describe the data best. The Madrid group RDWIA + QMC calculations diverge from the conventional RDWIA calculations as the virtuality moves further from zero. Calculations from Schiavilla are not available as a function of the missing momentum or the virtuality.

In summary, we have measured recoil polarization in the ${}^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ reaction at Q^2 values of 0.8 and 1.3 $(\mathrm{GeV}/c)^2$. The data agree well with previously reported measurements from Mainz [30] and JLab [31], but the increased precision challenges state-of-the-art nuclear physics calculations, both with and without medium modifications. Our data allow one to study the dependence of polarization-transfer ratios as functions of missing momentum and, for the first time, proton virtuality. The data are in excellent agreement with model calculations including the medium modification of the proton form factors through the quark-meson coupling model presented by Lu *et al.* [8] and with a chiral quark soliton model by Smith and Miller [14]. A model calculation by Schiavilla [17], which uses conventional free-space nucleon form factors but employs a different treatment of in-medium nucleon interactions, including charge-exchange processes, also agrees with the overall reduction of the polarization-transfer ratios, albeit within large uncertainties. Combining these data with similar precision induced-polarization data, directly sensitive to the number of in-medium nucleon interactions, may lead to a definite statement in favor

TABLE II. Values for the polarization-transfer coefficients P'_x and P'_z of the ejected proton from the listed target at both four-momentum transfer settings. Uncertainties are listed as statistical and then systematic. Systematic uncertainties in the ratios $(P'_x)_{\mathrm{He}}/(P'_x)_{\mathrm{H}}$ and $(P'_z)_{\mathrm{He}}/(P'_z)_{\mathrm{H}}$ and the double ratio R mostly cancel, providing a systematic precision better than 5.0×10^{-4}.

Q^2 $(\mathrm{GeV}/c)^2$	$(P'_x)_{\mathrm{He}}/(P'_x)_{\mathrm{H}}$	$(P'_z)_{\mathrm{He}}/(P'_z)_{\mathrm{H}}$	$\mu G_E/G_M$	R
0.8	1.062 ± 0.009	0.956 ± 0.010	0.901 ± 0.007 ± 0.010	0.900 ± 0.012
1.3	1.064 ± 0.014	0.954 ± 0.015	0.858 ± 0.008 ± 0.019	0.897 ± 0.019

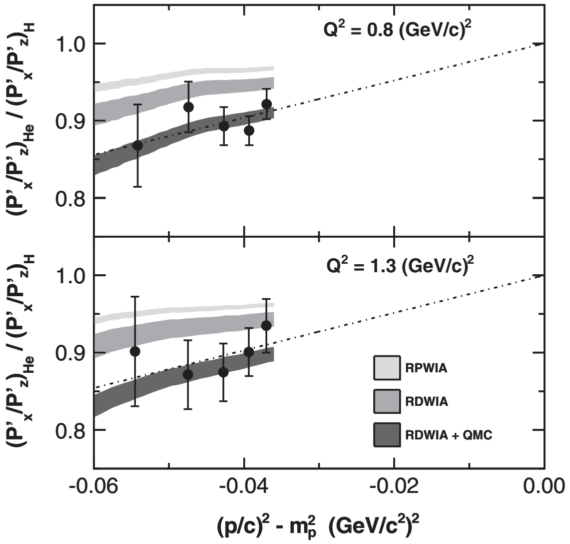

FIG. 3. The double ratio R versus the proton virtuality for $Q^2 = 0.8$ and 1.3 (GeV$/c$)^2. The dashed line is a linear fit to the data constrained to have a y intercept value of one at zero virtuality. The bands represent RPWIA (light gray), RDWIA calculations (gray), and RDWIA + QMC calculations (dark gray) [25]. See the text for a description of the models.

of or against the effective use of proton medium modifications.

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