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

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Proton recoil polarization was measured in the quasielastic $^4\text{He}(e,e'p)^3\text{H}$ reaction at $Q^2 = 0.8$ and 1.3 (GeV/c)$^2$ with unprecedented precision. The polarization-transfer coefficients are found to differ from those of the $^1\text{H}(e,e'p)^1\text{H}$ 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 $P_L/P_T$ 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 medium modification of nucleon structure; for recent examples, see [10,11]. In addition to the QMC model, many other model calculations predict the in-medium modification effects is expected. Additional $^1\text{H}(\bar{e}, e'\bar{p})$ 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 $^1\text{H}(\bar{e}, e'\bar{p})$ data.

Kinematic settings for the present experiment are given in Table I. For both $^1\text{H}(\bar{e}, e'\bar{p})$ and $^4\text{He}(\bar{e}, e'\bar{p})^3\text{H}$, the scattered electron and ejected proton were detected in coincidence in two high-resolution spectrometer arms. For the nine $^1\text{H}$ 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 $^4\text{He}(\bar{e}, e'\bar{p})^3\text{H}$ scattering. This allows for detailed studies of the spin transport and other instrumental effects. Beam currents up to 80 $\mu$A 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 $^4\text{He}(\bar{e}, e'\bar{p})^3\text{H}$ scattering, tight cuts on the reconstructed missing mass spectrum were used to ensure that quasielastic knockout of the proton leaves the undetected $^3\text{H}$ intact. Radiative effects due to single-photon emission [21], as well as radiative corrections from two-photon exchange to the polarization ratio $P'_r/P'_z$ [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,

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**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, $\theta_p$ is the central angle setting for the proton spectrometer, $p_e$ is the central momentum setting of the electron spectrometer, and $\theta_e$ is the central angle setting for the electron spectrometer.

<table>
<thead>
<tr>
<th>Kinematic setting</th>
<th>$Q^2$ (GeV/c)$^2$</th>
<th>$E_0$ (GeV)</th>
<th>Target</th>
<th>$p_p$ (GeV/c)</th>
<th>$\theta_p$ (deg)</th>
<th>$p_e$ (GeV/c)</th>
<th>$\theta_e$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1–9</td>
<td>0.8</td>
<td>1.987</td>
<td>$^1\text{H}$</td>
<td>0.991 ± 8%</td>
<td>50.668</td>
<td>1.561</td>
<td>−29.440</td>
</tr>
<tr>
<td>A10</td>
<td>0.8</td>
<td>1.987</td>
<td>$^4\text{He}$</td>
<td>1.004</td>
<td>49.115</td>
<td>1.532</td>
<td>−29.730</td>
</tr>
<tr>
<td>B1–9</td>
<td>1.3</td>
<td>2.637</td>
<td>$^1\text{H}$</td>
<td>1.334 ± 8%</td>
<td>45.289</td>
<td>1.944</td>
<td>−29.221</td>
</tr>
<tr>
<td>B10</td>
<td>1.3</td>
<td>2.637</td>
<td>$^4\text{He}$</td>
<td>1.353</td>
<td>43.920</td>
<td>1.909</td>
<td>−29.462</td>
</tr>
</tbody>
</table>
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 $^{4}\text{He}(\vec{e}, e'\vec{p})^{3}\text{H}$ normalized to the $^{1}\text{H}(\vec{e}, e'\vec{p})$ reaction, $(P'_{z})_{\text{He}}/(P'_{z})_{\text{H}}$ and $(P'_{z})_{\text{He}}/(P'_{z})_{\text{H}}$, and the double ratio $R$ are shown along with acceptance-corrected calculations from the Madrid group [23,24]. Here, $R$ is defined as

$$ R = \frac{(P'_{z})_{\text{He}}}{(P'_{z})_{\text{H}}}. \quad (1) $$

The Madrid group calculations use a relativistic wave function for the bound state that reproduces the exclusive $^{4}\text{He}(e, e'p)$ 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 $P'_{z}/P'_{x}$. One would expect a decrease for $(P'_{z})_{\text{He}}/(P'_{z})_{\text{H}}$ and an increase for $(P'_{z})_{\text{He}}/(P'_{z})_{\text{H}}$, 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.
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 $^1$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 $^4$He($\vec{e}, e'\vec{p})$ and $^4$He($\vec{e}, e'\vec{p})^3$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 $\nu = p^2 - m_p^2$. Here, $p$ is the proton four-momentum in the $^4$He nucleus and is defined as $p^2 = (m_{^4}\text{He} - E_i)^2 - \vec{p}_i^2$ in the impulse approximation, where $E_i$ and $p_i$ are, respectively, the energy and momentum of the undetected triton. The dashed line is a linear fit to the data assuming $R = 1$ at $\nu = 0$ 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 $^4$He($\vec{e}, e'\vec{p})^3$H reaction at $Q^2$ values of 0.8 and 1.3 (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

![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 + QCS (dash-dotted) calculations with the current operator $ee2$ and the MRW optical potential [25]. The gray band represents Schiavilla’s model [17]; see text for details.](image)
of or against the effective use of proton medium modifications.

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[2] With the initial and final electron energy given as $k_j$ and $k_f$, the coordinate system is given by $\hat{z} = (\hat{k}_j - \hat{k}_f)/|\hat{k}_j - \hat{k}_f|$, $\hat{y} = (\hat{k}_j \times \hat{k}_f)/|\hat{k}_j \times \hat{k}_f|$, and $\hat{x} = \hat{y} \times \hat{z}$.
[29] Prior publications from E93-049 have reported the $R$ ratio normalized to the PWIA. For simplicity in presentation, this text does not use that normalization.