

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

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The recoil polarization was measured in the ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ reaction at $Q^2 = 0.8$ (GeV/c) 2 and 1.3 (GeV/c) 2 . The ratio of polarization transfer coefficients is found to differ from a relativistic distorted wave approximation, favoring either the inclusion of a medium modified proton form factor predicted by the quark meson coupling model, or favoring a spin-dependent charge-exchange final state interaction.

PACS numbers:

1 Electron-nucleon scattering is a powerful tool for prob- 19 P'_x/P'_z .

2 ing the structure of nucleons. Over the last decade, ac- 20
3 cess to high-quality polarized electron beams has allowed 21
4 the electromagnetic properties of the nucleon to be ex- 22
5 plored through the polarization-transfer technique. Un- 23
6 like the Rosenbluth separation technique, which relies on 24
7 repeated cross section measurements, the polarization- 25
8 transfer technique provides information on the ratio of 26
9 the Sachs form factors G_E/G_M through polarization 27
10 measurement of an ejected nucleon in A(e,e'N)B type 28
11 reactions. 29

12 In elastic electron-nucleon scattering, the ratio 30
13 G_E/G_M is directly proportional to the ratio of trans- 31
14 verse and longitudinal polarization observables P'_x/P'_z in 32
15 the single-photon exchange approximation [1, 2]. Many 33
16 recent experiments have successfully extracted G_E/G_M 34
17 using this method [3–6]. In quasielastic nucleon knock- 35
18 out, the ratio G_E/G_M is expected to remain sensitive to 36

Due to the rich and complex nature of in-medium nucleon interactions, there have been proposed many models predicting both conventional and unconventional many-body effects. Questions of how and if nucleon structure is modified in-medium is a hotly debated topic in the nuclear physics community; for a recent review of medium modification studies, see Saito, Tsushima and Thomas [7]. A deviation in the electric and magnetic form factors G_E and G_M of a nucleon immersed in nuclear media from its free space equivalent is predicted by Lu *et al.* [8] using the quark-meson coupling (QMC) model. Predictions from Schiavilla [9] contend that final state interactions and meson exchange currents, including charge exchange processes, lead to a quenching of $\approx 10\%$ in the polarization transfer ratio P'_x/P'_z in the quasielastic scattering reaction ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$. Ciofi degli Atti *et al.* predict the proton G_E and G_M to be

strongly correlated to the excitation of the residual system and the virtuality of the ejected proton [10].

Previously, polarization transfer for the ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ reaction has been studied at $Q^2 = 0.4$ (GeV/c)² [11], 0.5 (GeV/c)², 1.0 (GeV/c)², 1.6 (GeV/c)², and 2.6 (GeV/c)² [12]. Fully modern theoretical models, both with and without QMC medium modified proton form factors, were tested against the data. The combined results favored models including medium modification; however, the $Q^2 = 1.6$ (GeV/c)² data alone was described well only by models without QMC medium modification. Although the data at $Q^2 = 1.6$ (GeV/c)² falls justifiably within statistical fluctuation, additional high-precession data at intermediate Q^2 was deemed necessary to clarify the world data picture.

This article reports on the ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ reaction scattering experiment E03-104 performed at Jefferson Lab Hall A. Data were taken at $Q^2 = 0.8$ and 1.3 (GeV/c)² within a missing momentum range < 160 MeV/c. The ${}^4\text{He}$ target nucleus was chosen for its uniformly high nuclear density and relative theoretical modeling simplicity. Recent studies of the EMC effect [13] have shown the effect on nucleons in ${}^4\text{He}$ is comparable to the effect on nucleons in ${}^{12}\text{C}$. The low missing momentum regime was chosen for its reduced contribution to many-body effects, although a weaker contribution of in-medium modification effects were expected. Additional ${}^1\text{H}(\vec{e}, e'\vec{p})$ scattering data was also taken to provide free-space unmodified proton scattering measurements as a base comparison.

Kinematic settings for the present experiment are given in Table 1. For both ${}^1\text{H}(\vec{e}, e'\vec{p})$ and ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$, the scattered electron and ejected proton are detected in coincidence in two high resolution spectrometer arms. For the ${}^1\text{H}$ kinematics, the central momentum settings for the proton were adjusted in 2% increments from -8% to $+8\%$ in order to produce similar coverage of the focal plane as in ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ scattering. This ensures that measured polarization observables for ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ and ${}^1\text{H}(\vec{e}, e'\vec{p})$ are similarly affected by instrumental uncertainties across the focal plane. The experiment used beam currents from 40 μA to 80 μA and beam polarizations of 85%. The proton spectrometer was equipped with a focal plane polarimeter (FPP) which measures the asymmetry of scattered polarized protons off of a Carbon analyzer [14]. The total spin precession of the proton from the target to the focal plane through the spectrometer arm's magnetic fields was calculated using COSY software [15]. A maximum likelihood method was then employed in conjunction with the beam helicity and polarimetry data to extract the polarization of the ejected proton at the target [16]. For ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ scattering, tight cuts on the reconstructed missing mass spectrum were used to ensure quasi-elastic knockout of the proton leaves an undetected ${}^3\text{H}$ intact.

Figures 1 and 2 provide our results for the polarization-transfer coefficients as a function of the missing momen-

tum. Here the individual polarization-transfer coefficients P'_x and P'_z for ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ and the double ratio R is shown along with acceptance corrected calculations from the Madrid group [17, 18]. Here R is defined as:

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

The Madrid group calculations included in this work use the nuclear current conservation conventions *cc1* and *cc2* [19], and optical potential models MRW [20] and RLF [21]. The green curves represents relativistic plane wave impulse approximation (PWIA) calculations, the blue curves represent a relativistic distorted-wave impulse approximation (RDWIA) calculation, and the red curve represents an RPWIA that includes an in-medium modified form-factor as predicted by Lu *et al* with the QMC model [8]. At both Q^2 0.8 (GeV/c)² and 1.3 (GeV/c)² the RPWIA calculation overestimates the data by greater than 10%. The RDWIA calculation better describes the data, but still overestimates our results by $\approx 5\%$. With RDWIA + QMC, the calculation is in much better agreement with the data. The difference in model wave functions, spinor distortions, current operators, and optical potentials do not constitute a large enough effect to describe the data from a conventional RDWIA. The RDWIA calculations including medium modified proton form factors show excellent agreement with the data. The RDWIA calculations with medium modified nucleon form-factors predict a greater divergence from standard RDWIA calculations at missing momentum further from zero. While confirmation of this trend is outside the scope of this body of work, an additional experiment, with tight control over FSI effects, could strongly test the competing models presented here.

In Figure 3, results are shown as the polarization-transfer double-ratio R plotted versus Q^2 . The results agree with previous results from Mainz [11] and JLab experiment E93049 [12]; additionally, the calculated G_E/G_M for ${}^1\text{H}(\vec{e}, e'\vec{p})$ agree with well with previous data [3–6]. The results for $\mu G_E/G_M$ for $Q^2 = 0.8$ (GeV/c)² and $Q^2 = 1.3$ (GeV/c)² are in strong agreement with world data. The experimental results for R are also listed in Table II. With data collection of ${}^1\text{H}(\vec{e}, e'\vec{p})$ and ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ under near identical experimental conditions, calculating the double-ratio R results in a significant cancellation of systematic uncertainties.

Theoretical calculations from Schiavilla [9] are included in Figure 3 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 with respect to Q^2 . Schiavilla's calculation includes MEC effects that suppress R by 4% and include both a spin-dependent and a spin independent charge exchange term in the final state interaction; all of which are not included in the Madrid group calculations.

Measurements of the induced polarization are useful for discerning between medium effects and final-state interactions. The induced polarization in the one-photon exchange approximation should be uniformly zero in the absence of final state interactions. Neither the Madrid group's RDWIA+QMC or Schiavilla's model calculations describe the data sufficiently to discern between models. See preliminary results on induced polarization measurements from E03-104 for a more in-depth analysis [22].

Figure 5 shows R as a function of the proton virtuality, $v = p^2 - m^2$. The black dashed line is a first-order polynomial fit to the data set to cross R at $v = 0$, and is included as a simplistic approximation of the expected trend in virtuality. Once again, the RDWIA models including medium modified proton form factors best describe the data. The Madrid group RDWIA + QMC calculations diverge from the conventional RDWIA calculations as virtuality moves further from zero.

In summary, we have measured recoil polarization in the ${}^4\text{He}(\bar{e}, e'\bar{p}){}^3\text{H}$ reaction at Q^2 values of $0.8 (\text{GeV}/c)^2$ and $1.3 (\text{GeV}/c)^2$. The data agrees well with previous reported measurements from Mainz [11] and JLab [12]. We have shown that our data supports model calculations including the medium modification of the proton form-factors through the quark-meson coupling model presented by Lu *et al* [8], as well as a model calculation by Schiavilla [9] which contains many-body effects, such as a spin-dependent charge exchange mechanism, and free-space nucleon form-factors. These data provide unprecedented statistics and the most up to date analysis of nucleon form-factor medium modification using the polarization-transfer technique.

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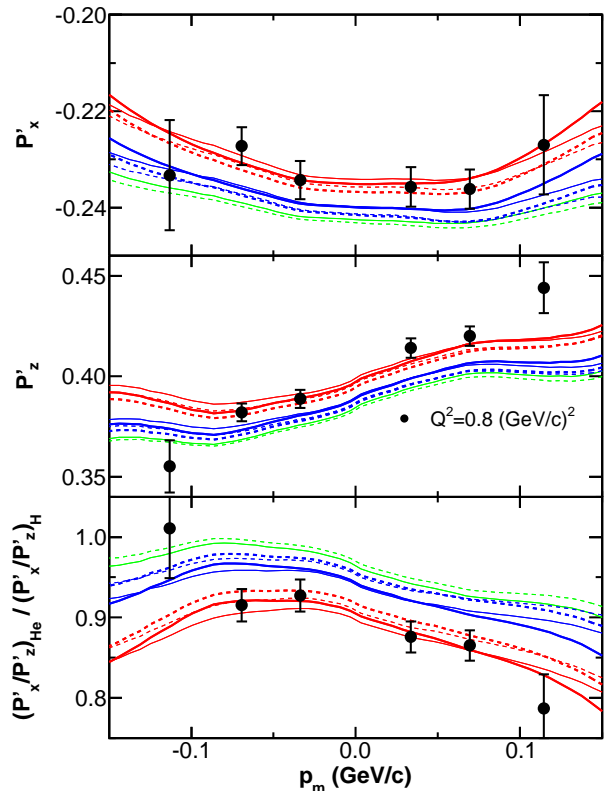


FIG. 1: The individual polarization-transfer coefficients, P'_x and P'_z , from ${}^4\text{He}(\bar{e}, e'\bar{p}){}^3\text{H}$, and the double-ratio $(P'_x/P'_z)_{\text{He}} / (P'_x/P'_z)_{\text{H}}$ versus the missing momentum p_m for $Q^2 = 0.8 (\text{GeV}/c)^2$. The curves represent PWIA (green), RDWIA calculations (blue), and RDWIA + QMC calculations (red). See the text for a description of the models. The uncertainties shown are statistical only; an additional systematic uncertainty of 0.003, 0.005 is expected for P'_x , and P'_z respectively.

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Kinematic Setting	Q^2 (GeV/c) ²	E_0 (GeV)	Target	$p_{0,p}$ (GeV/c)	$\theta_{0,p}$ (deg)	$p_{0,e}$ (GeV/c)	$\theta_{0,e}$ (deg)
A1-9	0.8	1.987	¹ H	$0.991 \pm 8\%$	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	$1.334 \pm 8\%$	45.289	1.944	-29.221
B10	1.3	2.637	⁴ He	1.353	43.920	1.909	-29.462

TABLE I: Table of kinematic settings for Experiment E03-104. Here E_0 is the incident beam energy, $p_{0,p}$ is the central momentum setting of the proton spectrometer, $\theta_{0,p}$ is the central angle setting for the proton spectrometer, $p_{0,e}$ is the central momentum setting of the electron spectrometer, and $\theta_{0,e}$ is the central angle setting for the electron spectrometer.

Q^2 (GeV/c) ²	Target	P'_x	P'_z	$\mu G_E/G_M$	$R_{He/H}$
0.8	⁴ He	$-0.227 \pm 0.002 \pm 0.003$	$0.391 \pm 0.002 \pm 0.005$	-	$0.897 \pm 0.011 \pm 0.00$
0.8	¹ H	$-0.247 \pm 0.001 \pm 0.003$	$0.379 \pm 0.001 \pm 0.005$	$0.901 \pm 0.006 \pm 0.010$	-
1.3	⁴ He	$-0.201 \pm 0.002 \pm 0.003$	$0.467 \pm 0.004 \pm 0.013$	-	$0.881 \pm 0.017 \pm 0.00$
1.3	¹ H	$-0.222 \pm 0.001 \pm 0.003$	$0.462 \pm 0.002 \pm 0.013$	$0.849 \pm 0.007 \pm 0.019$	-

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 then systematic.

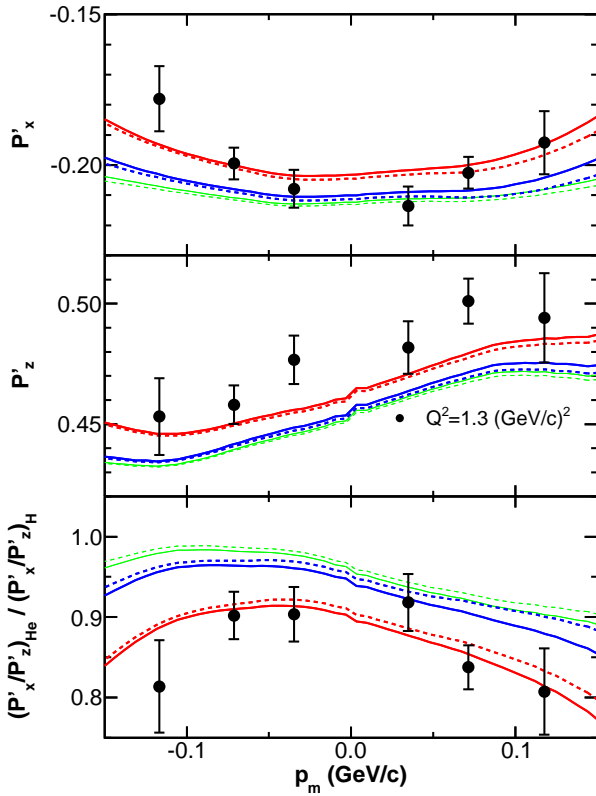


FIG. 2: The individual polarization-transfer coefficients, P'_x and P'_z , from ${}^4\text{He}(\bar{e},e'\bar{p}){}^3\text{H}$, and the double-ratio $(P'_x/P'_z)_{\text{He}}/(P'_x/P'_z)_{\text{H}}$ versus the missing momentum p_m for $Q^2 = 1.3$ (GeV/c)². The curves represent PWIA (green), RDWIA calculations (blue), and RDWIA + QMC calculations (red). See the text for a description of the models. The uncertainties shown are statistical only; an additional systematic uncertainty of 0.003, 0.013 is expected for P'_x , and P'_z respectively.

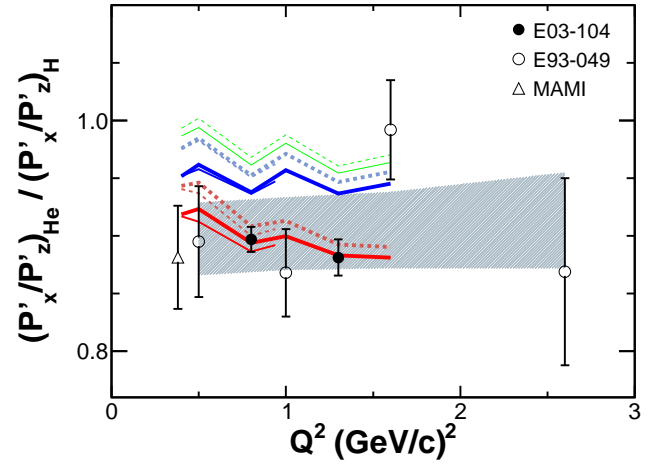


FIG. 3: Experimental results for $\mathcal{R}_{\text{He/H}}$ versus Q^2 for E03-104 (black circles), E93-049 (open circles) and MAMI (open triangle). The curves represent PWIA (green), RDWIA (blue), and RDWIA + QMC (red) calculations, $cc1$ (solid) and $cc2$ (dashed) current operators, and MRW (thick) and RLF (thin) optical potentials. The grey band represents a model that takes into account a spin-dependent charge exchange final state interaction.

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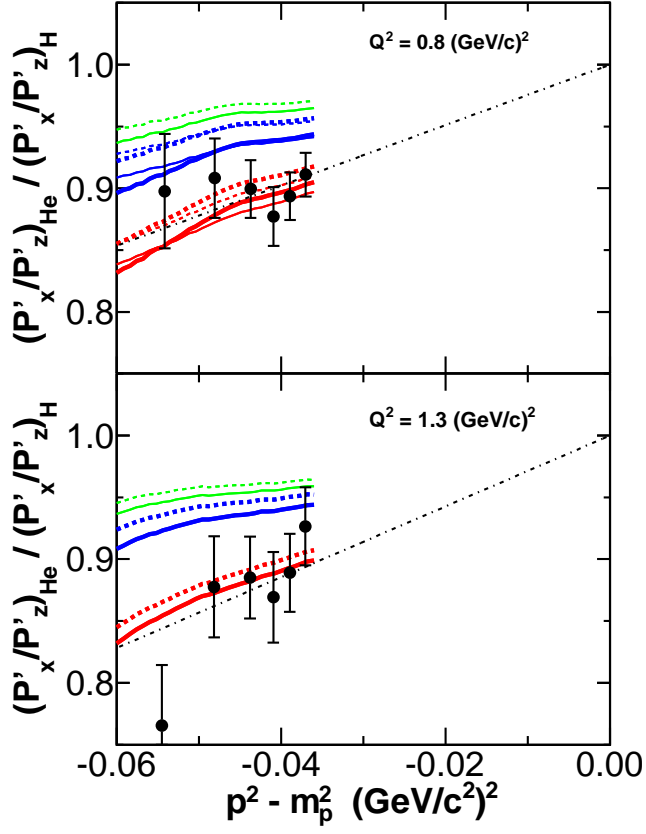


FIG. 4: The double ratio $(P'_x/P'_z)_{\text{He}}/(P'_x/P'_z)_{\text{H}}$ versus the proton virtuality for $Q^2 = 0.8$ and 1.3 $(\text{GeV}/c)^2$. The black dash-dot line is a linear fit of the data forced through a y intercept value of one. The curves represent RDWIA calculations (blue), and RDWIA + QMC calculations (red). See the text for a description of the models.