

Search for Proton Medium Modifications in the ${}^4\text{He}(\vec{e}, e' \vec{p}){}^3\text{H}$ Reaction

S. Strauch for the Jefferson Lab Hall A Collaboration

University of South Carolina, Columbia, South Carolina 29208, USA

Abstract. Polarization transfer in quasi-elastic nucleon knockout is sensitive to the properties of the nucleon in the nuclear medium, including possible modification of the nucleon form factor and/or spinor. In our recently completed experiment E03-104 at Jefferson Lab we measured the proton recoil polarization in the ${}^4\text{He}(\vec{e}, e' \vec{p}){}^3\text{H}$ reaction at a Q^2 of $0.8 (\text{GeV}/c)^2$ and $1.3 (\text{GeV}/c)^2$ with unprecedented precision. These data complement earlier data between 0.4 and $2.6 (\text{GeV}/c)^2$ from both Mainz and Jefferson Lab. The measured ratio of polarization-transfer coefficients differs from a fully relativistic calculation, favoring either the inclusion of a medium modification of the proton form factors predicted by a quark-meson coupling model or strong charge-exchange final-state interactions. The measured induced polarizations agree well with the fully relativistic calculation and indicate that these strong final-state interactions may not be applicable.

Keywords: proton recoil polarization, medium modification, final-state interactions

PACS: 13.40.Gp, 13.88.+e, 25.30.Dh, 27.10.+h

INTRODUCTION

The observation of neutrinos involves the measurement of secondary particles they create when interacting with nuclear targets. The analysis of these data requires thus a reliable understanding of the neutrino-nucleus reaction; see *e.g.* the calculations by Szczerbinska *et al.* [1] and Benhar *et al.* [2]. The advent of high-intensity neutrino beams makes neutrino experiments with increased statistical precision possible and put strong demands on the reduction of systematic uncertainties related to the modeling of neutrino interactions.

Relativity and final-state interactions (FSI) are two essential model ingredients for a successful description of the electroweak cross sections [3]. A model ingredient which is not often considered are possible modifications of the internal structure of nucleons bound in the nuclear medium. However, a calculation by Lu *et al.* [4], using a quark-meson coupling (QMC) model, suggests a measurable deviation from the free-space electromagnetic form-factor over the Q^2 range $0.0 < Q^2 < 2.5 (\text{GeV}/c)^2$. Similar measurable effects have recently been calculated in a light-front-constituent quark model by Frank *et al.* [5], a modified Skyrme model by Yakshiev *et al.* [6], a chiral quark-soliton model by Smith and Miller [7], and the Nambu-Jona-Lasinio model of Horikawa and Bentz [8]. The connection between the modifications induced by the nuclear medium of the nucleon form factors and of the deep inelastic structure functions is discussed by Liuti [9] using the concept of generalized parton distributions.

Tsushima, Kim, and Saito have applied the QMC model to calculate the effect of bound nucleon form factors on charged-current neutrino-nucleus scattering [10]. They estimate the effect on the inclusive ${}^{12}\text{C}(\nu_\mu, \mu^-)X$ cross section and find a reduction of

$\approx 8\%$ for the total cross section. The correction due to the in-medium form factors could indeed be significant for a precise estimate of the charged-current neutrino-nucleus cross section.

Electron-nucleus scattering data provide strong constraints on nuclear modeling of neutrino reactions. The polarization-transfer in quasielastic nucleon knockout, $(\vec{e}, e'\vec{N})$, is sensitive to the properties of the nucleon in the nuclear medium, including possible modification of the nucleon form factor and/or spinor. This reaction is also believed to have minimal sensitivity to reaction-mechanism effects; see, *e.g.*, [11]. In free electron-nucleon scattering, the ratio of the electric to magnetic Sachs form factors, G_E and G_M , is given by [12]:

$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z} \cdot \frac{E_e + E_{e'}}{2m_p} \tan\left(\frac{\theta_e}{2}\right). \quad (1)$$

Here, P'_x and P'_z are the transferred polarizations, transverse and longitudinal to the proton momentum. The beam energy is E_e , the energy (angle) of the scattered electron is $E_{e'}$ (θ_e), and m_p is the proton mass.

In the following, the results of ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ experiments to study the proton knockout process will be discussed. In these experiments ${}^4\text{He}$ was chosen as target because of its high density and relatively simple structure, which facilitate microscopic calculations.

EXPERIMENTS

The first ${}^4\text{He}(e, e'\vec{p}){}^3\text{H}$ polarization-transfer measurements were performed at the Mainz microtron (MAMI) at a four-momentum squared $Q^2 = 0.4 \text{ (GeV/c)}^2$ [13] and as experiment E93-049 at Jefferson Lab Hall A at $Q^2 = 0.5, 1.0, 1.6$, and 2.6 (GeV/c)^2 [14]. Our recent experiment E03-104 [15] has extended these measurements with two high-precision points at $Q^2 = 0.8$ and 1.3 (GeV/c)^2 . The data were taken in quasielastic kinematics at low missing momentum with symmetry about the three-momentum-transfer direction to minimize conventional many-body effects in the reaction. In each experiment, two high-resolution spectrometers were used to detect the scattered electron and the recoiling proton. The missing-mass technique was employed to identify ${}^3\text{H}$ in the final state. The proton recoil-polarization observables were extracted by means of the maximum-likelihood technique, utilizing the azimuthal distribution of protons scattered by the graphite analyzer in a focal-plane polarimeter (FPP) [16].

Since these experiments were designed to detect differences between the in-medium polarizations compared with the free values, both ${}^4\text{He}$ and ${}^1\text{H}$ targets were used. The results of the measurements are expressed in terms of the polarization-transfer double ratio, in which the helium polarization ratio is normalized to the hydrogen polarization ratio measured in the identical setting:

$$R = \frac{(P'_x/P'_z)_{{}^4\text{He}}}{(P'_x/P'_z)_{{}^1\text{H}}}. \quad (2)$$

As a cross-check, the hydrogen results were also used to extract the free-proton form-factor ratio G_E/G_M , which was found to be in excellent agreement with previous polarization-transfer data [16, 17]. Nearly all systematic uncertainties cancel in R : the

polarization-transfer observables are to first order independent of instrumental asymmetries in the FPP, and their ratio is independent of the electron-beam polarization and carbon analyzing power. Small systematic uncertainties are predominantly due to uncertainties in the spin transport through the proton spectrometer.

The induced proton polarization P_y in $(e, e' \vec{p})$ is a direct measure of final-state interactions and was also measured in the Jefferson Lab experiments. Its extraction is complicated by the presence of instrumental asymmetries.

RESULTS

The polarization-transfer double ratio, R , is shown in Figure 1. The preliminary data of the present experiment E03-104 (filled circles) are consistent with our previous data from E93-049 [14] and MAMI [13] (open symbols). The final systematic uncertainties from E03-104 are expected to be much smaller than those shown here. The data are compared with relativistic distorted-wave impulse approximation (RDWIA) calculations from the Madrid group [18]. The RDWIA calculation (dashed curve) overpredicts the data by about 6%. After including the density dependent medium-modified form factors as predicted by Lu *et al.* [4] in the RDWIA calculation (solid curve) good agreement with the previous data is obtained.¹ This agreement has been interpreted as a possible evidence of proton medium modifications [14]. This interpretation is based on the more effective description of the data in a particular model in terms of medium modifications of nucleon form factors and requires to have excellent control of the inherent many-body effects, such as meson-exchange currents (MEC) and isobar configurations (IC). In addition, when probing nuclear structure, one has to deal with final-state interactions (FSI). Indeed, the observed suppression of the polarization-transfer ratio has been equally well described in a more traditional calculation by Schiavilla [20] using free form factors by including charge-exchange final-state interactions and two-body charge and current operators (shaded band). Yet, the choice of the parameters for the charge-exchange FSI is not well constrained by data.

The preliminary results from E03-104 possibly hint at an unexpected trend in the Q^2 dependence of R . This is particularly interesting as other calculations of in-medium form factors suggest a different Q^2 dependence than that of the QMC model. The high statistics of the data from E03-104 will allow for a study of the individual polarization observables as a function of missing momentum up to about 120 MeV/c.

The difference in the modeling of final-state interactions is the origin of the major part of the difference between the results of the calculations by Udias *et al.* [18] and Schiavilla *et al.* [20] for the polarization observables. Effects from final-state interactions can be studied experimentally with the induced polarization, P_y . Figure 2 shows the data for P_y . The induced polarization is small in this reaction. The sizable systematic uncertainties are due to possible instrumental asymmetries. Dedicated data have been

¹ A Glauber-based calculations by Ryckebusch [19] gives R/R_{PWIA} of about one and is not shown here. We also do not show a chiral-soliton model calculation of the in-medium form factors by Smith and Miller [7], which give results similar to the QMC results.

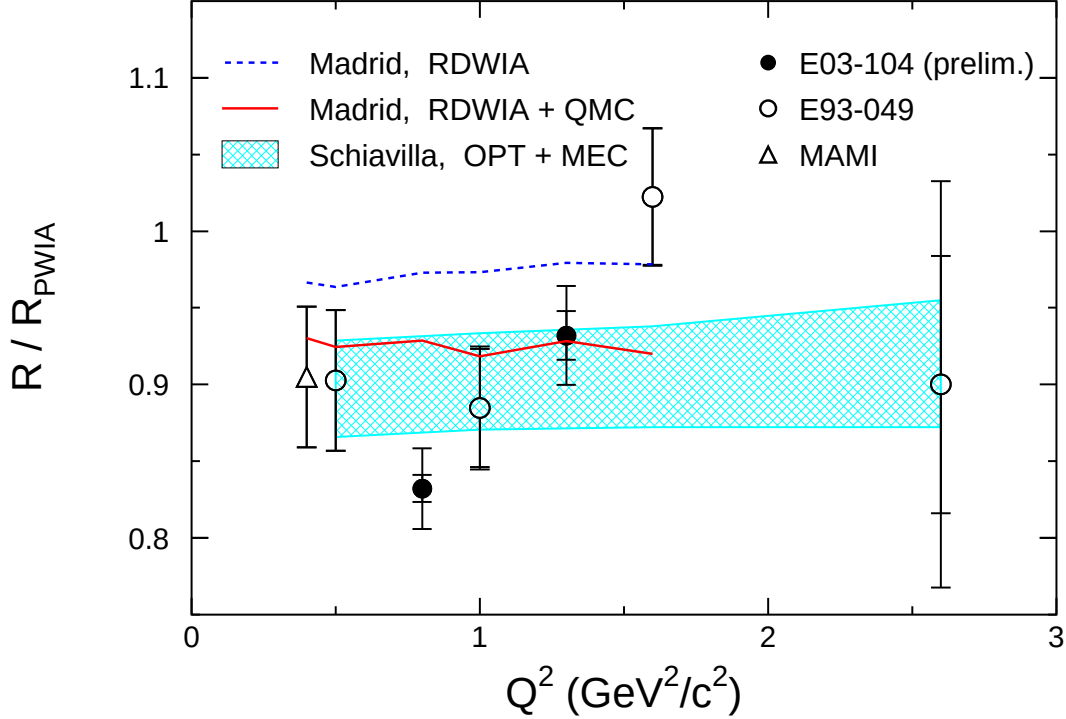


FIGURE 1. Superratio R/R_{PWIA} as a function of Q^2 from Mainz [13] and Jefferson Lab experiment E93-049 [14] (open symbols) along with preliminary results from experiment E03-104 (filled circles); R is the ratio of transverse to longitudinal polarization of the recoiling proton in ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ compared to the same ratio for ${}^1\text{H}(\vec{e}, e'\vec{p})$. The baseline R_{PWIA} is the value of R obtained in a plane-wave calculation, to account for the 'trivial' effects of free vs. moving proton. The data are compared to calculations from the Madrid group [18] and Schiavilla *et al.* [20].

taken during E03-104 to study these and we hope to significantly reduce the systematic uncertainties in P_y in the final analysis. The data are compared with the results of the calculations from the Madrid group and Schiavilla *et al.* at missing momenta of about zero. The data have been corrected for the spectrometer acceptance to facilitate this comparison. Presently, the data suggest that the magnitude of the induced polarization (and thus the final-state interaction) is overestimated in the model of Schiavilla *et al.*. A comparison of the model calculations in Figure 1 and Figure 2 shows that the in-medium form factors (solid curves) mostly affect the ratio of polarization-transfer observables, not the induced polarization. It is a key element of E03-104 to have access to both.

In summary, polarization transfer in the quasielastic $(e, e'p)$ reaction is sensitive to possible medium modifications of the bound-nucleon form factor, while at the same time largely insensitive to other reaction mechanisms. Currently, the ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$ polarization-transfer data can be well described by either the inclusion of medium-modified form factors or strong charge-exchange FSI in the models. However, these strong FSI effects may not be consistent with the induced polarization data. The final

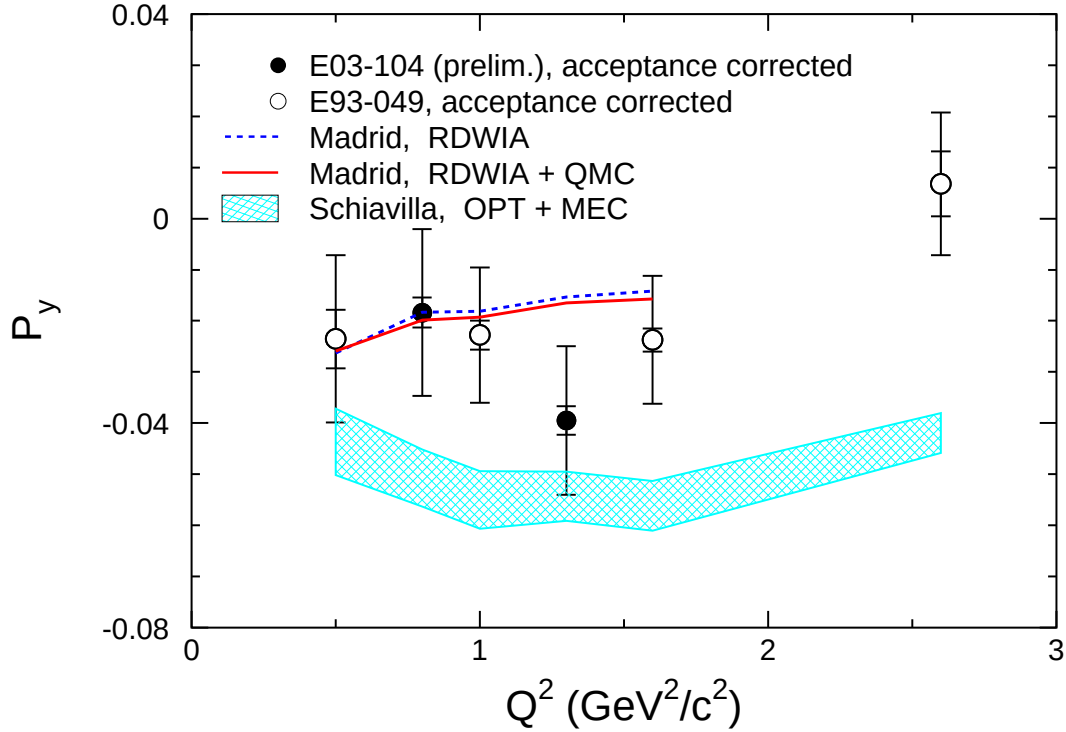


FIGURE 2. Induced polarization data from Mainz [13] and Jefferson Lab experiment E93-049 [14] along with preliminary results from experiment E03-104. The data are compared to calculations from the Madrid group [18] and Schiavilla *et al.* [20]. The comparison is made for missing momentum $p_m \approx 0$; note that the experimental data have been corrected for the spectrometer acceptance for this comparison.

analysis of our new high-precision data from Jefferson Lab Hall A should provide a more stringent test of these calculations.

ACKNOWLEDGMENTS

This work was supported in parts by the U.S. National Science Foundation: NSF PHY-0555604. Jefferson Science Associates operates the Thomas Jefferson National Accelerator Facility under DOE contract DE-AC05-06OR23177.

REFERENCES

1. B. Szczerbinska, T. Sato, K. Kubodera, and T.-S.H. Lee, Phys. Lett. B **649**, 132 (2007).
2. O. Benhar, N. Farina, H. Nakamura, M. Sakuda, and R. Seki, Phys. Rev. D **72**, 053005 (2005).
3. J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly, and J.M. Udias, Phys. Rev. C **75**, 034613 (2007).
4. D.H. Lu *et al.*, Phys. Lett. **B417**, 217 (1998) and Phys. Rev. C **60**, 068201 (1999).

5. M.R. Frank, B.K. Jennings, and G.A. Miller, Phys. Rev. C **54**, 920 (1996).
6. U.T. Yakhshiev, U-G. Meissner, and A. Wirzba, Eur. Phys. J. A **16**, 569 (2003).
7. J.R. Smith and G.A. Miller, Phys. Rev. C **70**, 065205 (2004).
8. T. Horikawa and W. Bentz, Nucl. Phys. A **762**, 102 (2005).
9. S. Liuti, arXiv:hep-ph/0601125v2.
10. K. Tsushima, H. Kim, and K. Saito, Phys. Rev. C **70**, 038501 (2004).
11. J.M. Laget, Nucl. Phys. A **579**, 333 (1994).
12. A.I. Akhiezer and M.P. Rekalo, Sov. J. Part. Nucl. **3**, 277 (1974); R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981).
13. S. Dieterich *et al.*, Phys. Lett. **B500**, 47 (2001).
14. S. Strauch *et al.*, Phys. Rev. Lett. **91**, 052301 (2003).
15. Jefferson Lab experiment E03-104, R. Ent, R. Ransome, S. Strauch, and P. Ulmer (spokespeople).
16. V. Punjabi *et al.*, Phys. Rev. C **71**, 055202 (2005).
17. M.K. Jones *et al.*, Phys. Rev. Lett. **84**, 1389 (2000); O. Gayou *et al.*, Phys. Rev. C **64**, 038202 (2001); O. Gayou *et al.*, Phys. Rev. Lett. **88**, 092301 (2002); G. Ron *et al.*, arXiv:0706.0128v1 [nucl-ex].
18. J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999); J.A. Caballero, T.W. Donnelly, E. Moya de Guerra, and J.M. Udias, Nucl. Phys. A **632**, 323 (1998); J.M. Udias and J.R. Vignote, Phys. Rev. C **62**, 034302 (2000).
19. P. Lava *et al.*, Phys. Rev. C **71**, 014605 (2005).
20. R. Schiavilla *et al.*, Phys. Rev. Lett. **94**, 072303 (2005).