Polarization Transfer in the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ Reaction up to $Q^2 = 2.6\ (\mathrm{GeV}/c)^2$

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(Received 6 November 2002; revised manuscript received 5 May 2003; published 29 July 2003)

We have measured the proton recoil polarization in the $^4\mathrm{He}(\vec{e}, e'\vec{p})^4\mathrm{H}$ reaction at $Q^2 = 0.5$, 1.0, 1.6, and 2.6 $(\mathrm{GeV}/c)^2$. The measured ratio of polarization transfer coefficients differs from a fully relativistic calculation, favoring the inclusion of a medium modification of the proton form factors predicted by a quark-meson coupling model. In addition, the measured induced polarizations agree reasonably well with the fully relativistic calculation indicating that the treatment of final-state interactions is under control.

DOI: 10.1103/PhysRevLett.91.052301 PACS numbers: 13.40.Gp, 13.88.+e, 25.30.Dh, 27.10.+h

The underlying theory of strong interactions is quantum chromodynamics, yet there are no *ab initio* calculations of nuclei available. Nuclei are effectively and well described as clusters of protons and neutrons held together by a strong, long-range force mediated by meson exchange, whereas the saturation properties of nuclear matter arise from the short-range, repulsive part of the strong interaction [1]. Whether the nucleon bound in the nuclear medium changes structure has been a long-standing issue in nuclear physics. At nuclear densities of about 0.17 nucleon/fm^3, nucleon wave functions have significant overlap. In the chiral limit, one expects nucleons to lose their identity altogether and nuclei to make a transition to a quark-gluon plasma.

Unfortunately, distinguishing possible changes in the structure of nucleons embedded in a nucleus from more conventional many-body effects is only possible within the context of a model. Nucleon modifications can be described in terms of coupling to nucleon excited states, and such changes are intrinsically intertwined with many-body effects, such as meson-exchange currents (MEC) and isobar configurations. Therefore, interpretation of an experimental signature as an indication of modifications of the nucleon form factors makes sense only if this results in a more economical effective description of the bound, quantum, nuclear many-body system.

The quark-meson coupling (QMC) model of Lu *et al.* [2] suggests a measurable deviation of the ratio of the proton's electric (G_E) and magnetic (G_M) form factors from its free space value over the Q^2 range accessible by experiment. This calculation is consistent with present experimental constraints on possible medium modifications for both G_E [from the Coulomb sum rule, with $Q^2 < 0.5\ (\mathrm{GeV}/c)^2$ [3–5]] and G_M [from a y-scaling analysis [6], for $Q^2 > 1\ (\mathrm{GeV}/c)^2$], and with limits on the scaling of nucleon magnetic moments in nuclei [7]. Similar effects have been calculated in the light-front constituent quark model of Frank *et al.* [8] and in the modified Skyrme model of Yakshiev *et al.* [9].

In unpolarized $A(e, e'p)$ experiments involving light and medium-heavy nuclei, deviations were observed in the longitudinal/transverse nuclear response compared to the free proton case [10–12]. Below the two-nucleon emission threshold, these deviations were originally interpreted as changes in the nucleon form factors within the nuclear medium. However, strong interaction effects on the ejected proton [final-state interactions (FSI)] later also succeeded in explaining the observed effect [13]. This illustrates that any interpretation in terms of medium modifications to nucleon form factors requires having excellent control of FSI effects.

For free electron-nucleon scattering, the ratio of the electric to magnetic Sachs form factors, (G_E/G_M), is directly proportional to the ratio of the transverse and longitudinal transferred polarizations, (P'_x/P'_z) [14,15]. This relationship was recently used to extract G_E/G_M for the proton [16–19]. Polarization transfer in quasielastic nucleon knockout remains sensitive to this ratio of form factors (possibly modified by the nuclear medium). A variety of calculations for the $A(\vec{e}, e'\vec{p})$ reaction indicate that FSI and MEC effects on polarization transfer observables are small, amounting to only a <10% correction [20–22]. In addition, these nuclear interaction effects tend to largely cancel in the ratio of polarization transfer coefficients P'_x/P'_z.

Recently, polarization transfer for the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ reaction at $Q^2 = 0.4\ (\mathrm{GeV}/c)^2$ was studied [23]. The addition of medium-modified proton form factors, as predicted by the QMC model, to a state-of-the-art fully relativistic model [21] gave a good description of the data. The authors concluded that, within the model space examined, the data favor models with medium-modified form factors over those with free form factors, but the latter could not be excluded. Examination of this finding over a larger range in Q^2 seems an obvious step for further investigation.

The experiment reported here measured the polarization transfer coefficients for $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ over the range of Q^2 from 0.5 to 2.6 $(\mathrm{GeV}/c)^2$, and as a function of missing momentum in the range 0 to 240 MeV/c. The ^{4}He nucleus was selected for study because its relative simplicity allows more realistic calculations and its high density enhances any possible medium effects. Selecting high Q^2 maximizes the sensitivity, in the context of [2], to possible medium effects of the electric to magnetic form-factor ratio for protons bound in the ^{4}He nucleus. Finally, restricting the missing momentum to fairly low values reduces sensitivity to various reaction mechanism effects not included in the models. As the experiment was designed to detect differences between the in-medium polarizations and the free values, both ^{4}He and ^{1}H targets were employed [except at $Q^2 = 2.6\ (\mathrm{GeV}/c)^2$, where only ^{4}He data were acquired due to beam time constraints].

Kinematics for the present experiment in Hall A at Jefferson Lab (JLab) are given in Table I. The experiment used beam currents of 40 μA for the lower Q^2 values and up to 70 μA for the highest Q^2 value, combined with beam polarizations of 66% for the lowest Q^2 value and $\approx 77\%$ for the other Q^2 values. The beam helicity was flipped pseudorandomly to reduce systematic errors of the extracted polarization transfer observables. The proton spectrometer was equipped with a focal plane polarimeter (FPP) [24,25]. Polarized protons lead to azimuthal asymmetries after scattering in the carbon analyzer of the FPP. These distributions, in combination with information on the beam helicity, were analyzed by means of a maximum likelihood method to obtain the induced and

TABLE I. Kinematics for the present experiment. For the electron and proton angles we indicate between parentheses the angles for the $^1\mathrm{H}(\vec{e}, e'\vec{p})$ reaction, if different from the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ reaction.

Beam energy (MeV)	Q^2 $[(\mathrm{GeV}/c)^2]$	Electron momentum (MeV/c)	Electron θ_{LAB} (degrees)	Proton momentum (MeV/c)	Proton θ_{LAB} (degrees)
3400	0.5	3102	12.47(12.50)	766	61.43(63.12)
4239	1.0	3667	14.56	1150	54.55(54.82)
4237	1.6	3340	19.35	1549	45.75(46.77)
4237	2.6	2796	27.10	2161	36.20

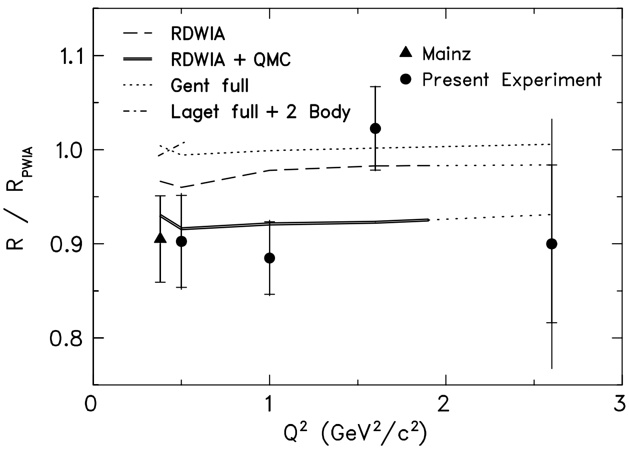

FIG. 1. Superratio R/R_{PWIA} as a function of Q^2. R is defined as the double ratio $(P'_x/P'_z)_{\mathrm{He}}/(P'_x/P'_z)_{\mathrm{H}}$. The short-dashed curve is the result of a calculation by the Gent Group [28,29]. The dot-dashed curve, at $Q^2 < 0.5\ (\mathrm{GeV}/c)^2$ only, shows the results of Laget's full calculation, including two-body currents [20]. The long-dashed curve shows the results of the full relativistic calculation of the Madrid Group [21]. The solid curve indicates the calculations of this Madrid Group including medium modifications as predicted by a quark-meson coupling model [2]. For $Q^2 > 1.8\ (\mathrm{GeV}/c)^2$ these calculations [21] maintain a constant relativistic optical potential and are extended as dotted curves. Lines connect the acceptance-averaged theory calculations.

transferred polarization components. More details on the analysis can be found in Refs. [16,26,27].

Our results are shown in Fig. 1 as the "superratio" R/R_{PWIA} for all four values of Q^2. R is the polarization double ratio

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

and R_{PWIA} is the same ratio in the relativistic plane-wave impulse approximation (RPWIA) calculation. In the double ratio R nearly all systematic uncertainties cancel. (As a cross check, the hydrogen results were also used to extract the free proton form-factor ratio G_E/G_M and were found to be in excellent agreement with previous data [16,17].) Our result for R/R_{PWIA} at $Q^2 = 0.5\ (\mathrm{GeV}/c)^2$ closely coincides with the recent results at $Q^2 = 0.4\ (\mathrm{GeV}/c)^2$ of Dieterich *et al.* [23], also shown in Fig. 1. Our experimental results for helium and hydrogen separately, in terms of (P'_x/P'_z), are tabulated in Table II. Systematic uncertainties are mainly due to possible minor misalignments of the magnetic elements of the proton spectrometer and uncertainties in the spin transport through these magnetic elements. They are estimated to contribute less than 1.7% to R.

The theoretical calculations by the Madrid Group [21] are averaged over the experimental acceptance. We note that these relativistic calculations provide good descriptions of, e.g., the induced polarizations measured at Bates in the $^{12}\mathrm{C}(e, e'\vec{p})$ reaction [30] and of the transverse-longitudinal asymmetry, A_{TL}, in $^{16}\mathrm{O}(e, e'p)$ as previously measured at JLab [31].

At $Q^2 = 0.5$ and $1.0\ (\mathrm{GeV}/c)^2$ the RPWIA calculation overestimates the data by $\approx 10\%$. The relativistic distorted-wave impulse approximation (RDWIA) calculation gives a slightly smaller ($\approx 3\%$) value of R but still overpredicts the data. After including the (density-dependent) medium-modified form factors as predicted by Lu *et al.* [2] in the RDWIA calculation, excellent agreement is obtained at both settings. All calculations shown use the Coulomb gauge, the $cc1$ current operator as defined in [32], and the McNeil, Ray, and Wallace (MRW) optical potential of [33]. The $cc2$ current operator gives slightly higher values of R, worsening agreement with the data. In general, various choices for, e.g., spinor distortions, current operators, and relativistic corrections, affect the theoretical predictions by $\leq 3\%$, and can presently not explain the disagreement between the data and the RDWIA calculations. In contrast, the datum at $Q^2 = 1.6\ (\mathrm{GeV}/c)^2$ is well described by the RPWIA and RDWIA calculations, whereas all calculations are consistent with the datum at $Q^2 = 2.6\ (\mathrm{GeV}/c)^2$.

A statistical analysis of the measured double ratios, including the result of the Mainz experiment [23], and various theoretical predictions was performed. The model space we examined encompassed the RPWIA and RDWIA calculations of [21], the latter with and without medium modifications as predicted by a QMC model [2], the full nonrelativistic model with explicit meson and isobar degrees of freedom of [28,29], and the full

TABLE II. Polarization ratios with statistical and estimated systematic uncertainties. The polarization ratio value for $^1\mathrm{H}(\vec{e}, e'\vec{p})$ at $Q^2 = 2.6\ (\mathrm{GeV}/c)^2$ is from the fit of Ref. [16]. The uncertainty in this ratio and in R reflects the typical systematic uncertainty of the data of Ref. [16] at this Q^2.

Q^2	$(P'_x/P'_z)_{\mathrm{He}}$	$(P'_x/P'_z)_{\mathrm{H}}$	R
0.5	$-0.804 \pm 0.035 \pm 0.006$	$-0.898 \pm 0.029 \pm 0.011$	$0.895 \pm 0.048 \pm 0.015$
1.0	$-0.502 \pm 0.018 \pm 0.005$	$-0.578 \pm 0.014 \pm 0.005$	$0.868 \pm 0.038 \pm 0.011$
1.6	$-0.393 \pm 0.014 \pm 0.011$	$-0.395 \pm 0.010 \pm 0.009$	$0.992 \pm 0.043 \pm 0.007$
2.6	$-0.231 \pm 0.022 \pm 0.016$	(-0.265 ± 0.024)	$0.869 \pm 0.081 \pm 0.099$

nonrelativistic calculation of Laget including two-body currents [20]. For the latter calculation only data up to $Q^2 = 0.5\ (\mathrm{GeV}/c)^2$ are taken into account. A significantly better description is given by the RDWIA calculation when medium modifications are included.

Figure 2 shows the polarization double ratio R as a function of missing momentum for the lower three Q^2 kinematics [the statistics at the $Q^2 = 2.6\ (\mathrm{GeV}/c)^2$ kinematics are not sufficient to make a meaningful comparison with calculations]. Negative values of missing momentum correspond to the recoiling nuclei having a momentum component antiparallel to the direction of the three-momentum transfer. Both the RPWIA and the RDWIA give a reasonable, but not perfect, description of the missing momentum dependence of the data. As already seen in Fig. 1, the difference in magnitude between the RDWIA calculation and the data at $Q^2 = 0.5$ and $1.0\ (\mathrm{GeV}/c)^2$ can be largely eliminated by including the QMC medium modifications, whereas at $Q^2 = 1.6\ (\mathrm{GeV}/c)^2$ the calculation without QMC medium modifications already gives a satisfactory description. More precise data are needed to settle whether this is just a statistical fluctuation.

Lastly, we show in Fig. 3 the induced polarization, P_y, obtained by averaging over the two beam helicities, and corrected for (small) false asymmetries, as a function of Q^2. P_y is identically zero in the absence of FSI effects (in the one-photon exchange approximation) and constitutes a stringent test of the validity of the inclusion of FSI effects in the calculations. An example of such an FSI effect is the charge exchange $(\vec{e}, e'\vec{n})(\vec{n}, \vec{p})$ reaction not included in the RDWIA calculations. Nonetheless, the measured induced polarizations agree well with the RDWIA calculations. In addition, the $^{12}\mathrm{C}(\vec{e}, e'\vec{p})$ and $^{16}\mathrm{O}(\vec{e}, e'\vec{p})$ reactions were calculated to be insensitive to this effect [22].

One sees in Fig. 3 that the induced polarizations are small for all measured Q^2 values. The dashed and solid bands represent RDWIA calculations by [21] with the MRW [33] and RLF [34] relativistic optical potentials. For the induced polarization case, the RDWIA curves with and without medium modifications are identical: as mentioned earlier the QMC model incorporates modifications only to the one-body form factors. For a rigorous calculation of the $^4\mathrm{He}(e, e'\vec{p})^3\mathrm{H}$ reaction under discussion here, one would need to take into account possible medium modifications to both one-body form factors and many-body FSI effects.

In summary, we have measured recoil polarization in the $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ reaction in the range from $Q^2 = 0.5$ to $2.6\ (\mathrm{GeV}/c)^2$. The datum at the lowest Q^2 agrees well with the results of a recently reported Mainz measurement [23]. Such polarization transfer data are calculated to be only slightly dependent ($< 10\%$ effect) on nuclear structure effects and fine details of the reaction mechanism. Furthermore, these effects tend to cancel in the P'_x/P'_z polarization transfer ratio. Within our model assumptions we find evidence for a medium modification; a calculation incorporating a predicted medium modification based on the quark-meson coupling model [2] gives a significantly improved though not perfect description of

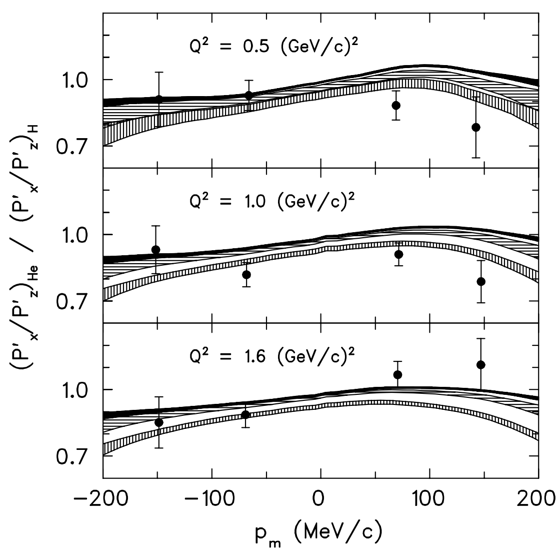

FIG. 2. Measured values of the polarization double ratio R for $^4\mathrm{He}(\vec{e}, e'\vec{p})^3\mathrm{H}$ at $Q^2 = 0.5\ (\mathrm{GeV}/c)^2$ (top), $Q^2 = 1.0\ (\mathrm{GeV}/c)^2$ (middle), and $Q^2 = 1.6\ (\mathrm{GeV}/c)^2$ (bottom). The shaded bands represent RPWIA calculations (solid), RDWIA calculations (horizontal dashes), and RDWIA calculations including QMC medium-modified form factors [2] of [21] (vertical dashes). The bands reflect variations due to choice of current operator, optical potential, and bound-state wave function (see also [23]).

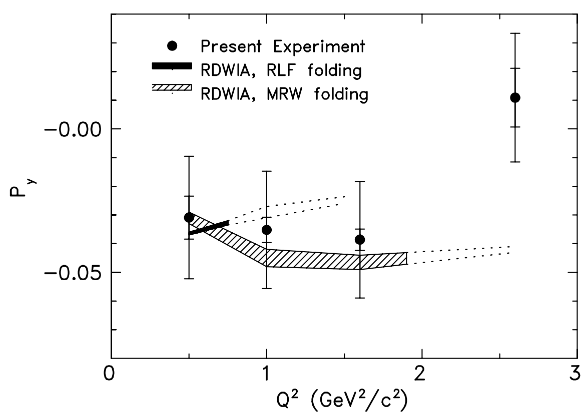

FIG. 3. Measured values of the induced polarizations for the $^4\mathrm{He}(e, e'\vec{p})^3\mathrm{H}$ reaction. The inner uncertainty is statistical only; the total uncertainty includes a systematic uncertainty of ± 0.02, due to imperfect knowledge of the false asymmetries. The solid and dashed bands show the results for the full relativistic RDWIA calculations of [21], using differing relativistic optical potentials and parameters [33,34]. The dotted lines indicate the Q^2 regions beyond the validity of the relativistic optical potentials used.

our data. Moreover, the calculated induced polarizations agree well with our data, giving credibility to the validity of the treatment of FSI effects in the model. These data provide the most stringent test to date of the applicability of conventional meson-nucleon calculations.

The collaboration wishes to acknowledge the Hall A technical staff and the Jefferson Lab Accelerator Division for their outstanding support. The Southeastern Universities Research Association (SURA) operates the Thomas Jefferson National Accelerator Facility for the United States Department of Energy under Contract No. DE-AC05-84ER40150. This work was supported by research grants from the United States Department of Energy and the National Science Foundation, the Italian Istituto di Fisica Nucleare (INFN), the Natural Sciences and Engineering Council of Canada (NSERC), the Swedish Natural Science Research Council, and the Comunidad de Madrid and Ministerio de Ciencia y Technologia (Spain).

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