A precise extraction of the induced polarization in the ^{4}He$(e, e'\vec{p})^3$H reaction

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We measured with unprecedented precision the induced polarization P_y in ^{4}He$(e, e'\vec{p})^3$H at $Q^2 = 0.8$ (GeV/c)^2 and 1.3 (GeV/c)^2. The induced polarization is indicative of reaction-mechanism effects beyond the impulse approximation. Our results are in agreement with a relativistic distorted-wave impulse approximation calculation but are over-estimated by a calculation with strong charge-exchange effects. Our data are used to constrain the strength of the spin independent charge-exchange term in the latter calculation.

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Whether the nucleon changes its fundamental properties while embedded in nuclear medium has been a longstanding question in nuclear physics, attracting experimental and theoretical attention. In this context, one of the hotly debated topics has been the interpretation of the quenching in the polarization-transfer double ratio, $(P_x^{'}/P_z^{'})_{^4He}/(P_x^{'}/P_z^{'})_{^1H}$ extracted from measurements of the polarization-transfer coefficients, $P_x^{'}$ and $P_z^{'}$, in elastic $\vec{e}p$ scattering and quasielastic scattering on ^{4}He [1–4]. In elastic $\vec{e}p$ scattering $P_x^{'}/P_z^{'}$ is directly proportional to the ratio of the electric and magnetic form factors of the proton, G_E/G_M [5]. In A$(\vec{e}, e'\vec{p})$B quasielastic scattering, the polarization-transfer ratio is expected to be sensitive to the form-factor ratio of the proton embedded in the nuclear medium. The polarization double ratio is then taken to emphasize differences between the in-medium and free values. For a ^{4}He nucleus this double ratio was found to be quenched by 10% [1, 4]. This quenching could be due to conventional nuclear medium effects like nucleon off-shellness, meson-exchange currents (MEC), final-state interactions (FSI) but also to unconventional effects like modifications of the electric and magnetic form factors of the proton in the nuclear medium [6]. However, interpreting a small quenching in the polarization transfer double ratio as evidence of unconventional nuclear effects requires excellent control of conventional reaction mechanisms. The induced polarization P_y, experimentally accesible along with P_x' and P_z', is a measure of conventional nuclear effects and offers vital constraints for the interpretation of the polarization-transfer double ratio.

The polarization-transfer double ratio from Jefferson Lab experiments E93-049 [1] and E03-104 [4] has been successfully modeled by two competing theoretical predictions: the relativistic distorted wave impulse approximation (RDWIA) calculation by the Madrid group [2] with medium-modified form factors from the quark-meson coupling (QMC) model [6], and the calculation of Schiavilla *et al.* [3] which assumes free nucleon form factors but has different modeling of nuclear conventional effects, in particular the FSIs. Whether the two models give an accurate description of P_y has become the key in the interpretation of the polarization-transfer double ratio. The large uncertainties of E93-049 P_y measurements precluded any definite conclusion. Experiment E03-104 provides the most precise measurements to date of the induced polarization in $^4\mathrm{He}(e,e'\vec{p})^3\mathrm{H}$ and this letter presents the results.

We report measurements of the induced polarization P_y in the quasi-elastic reaction $^4\mathrm{He}(e,e'\vec{p})\,^3\mathrm{H}$, at four-momentum transfer, Q^2, of 0.8 and 1.3 $(\mathrm{GeV}/c)^2$ and missing momentum, p_m, ranging from 0 to 160 MeV/c. A longitudinally polarized electron beam with flipping polarization direction and a current of 80 μA was incident on ^{4}He and ^{1}H targets and the scattered electron and recoil proton were detected in coincidence in two high-resolution spectrometer arms. The ^{4}He target was chosen because its relative simplicity allows for realistic microscopic theoretical calculations while its high nuclear density increases the sensitivity to nuclear medium effects. The proton arm central momenta for the $^1\mathrm{H}(\vec{e},e'\vec{p})$ reaction were adjusted in 2% increments from -8% to +8% so that protons in elastic $\vec{e}p$ scattering had a similar coverage of the focal plane as in the $^4\mathrm{He}(\vec{e},e'\vec{p})\,^3\mathrm{H}$ reaction [4]. These $\vec{e}p$ measurements provided a baseline for the comparison of in-medium to free proton polarizations and were also used to check for possible instrumental asymmetries.

The polarized recoil protons traveled through the magnetic field of the spectrometer to the detector package used to measure the polarizations, the focal plane polarimeter (FPP) [7]. The spin precession of the protons was calculated using a well established model of the spectrometer's magnetic field [4]. In the FPP, the polarized protons scattered in a carbon block leading to azimuthal asymmetries. These asymmetries in combination with information on the proton spin precession and the carbon analyzing power were analyzed by means of a maximum likelihood method to obtain the induced polarization [8].

The extraction of the induced polarization P_y is complicated by the presence of instrumental asymmetries. For the particular reaction that we studied, P_y was expected to be small, $< 6\%$ [1]. Thus even small instrumental asymmetries could constitute a significant background. The ^{1}H data have been used to check for the presence of instrumental asymmetries. In the one-photon-exchange approximation P_y in $^1\mathrm{H}(e,e'\vec{p})$ is expected to be zero. The two-photon-exchange processes could yield a non-zero but rather small induced polarization, theoretical calculations predicting a value below 1% [9, 10] at our kinematics. When taking into account the analyzing power and the recoil proton spin transport, this will translate into an expectation for the physics azimuthal asymmetries of $< 0.4\%$ making any significant instrumental asymmetries easy to detect.

We performed an extensive study to identify and correct for these asymmetries. The azimuthal distributions of the polarized protons are reconstructed from the track information provided by the FPP straw chambers located before (front) and after (rear) the carbon analyzer [7]. We engaged in a thorough check of the performance of the chambers and we found that inefficient regions and misalignments of the front and rear chambers lead to a contamination of the physics asymmetries. We devised a new tracking algorithm to allow track reconstruction even in inefficient regions and we developed a more precise alignment procedure to correct for misalignments. Our studies lead to experimental azimuthal asymmetries for $^1\mathrm{H}(e,e'\vec{p})$ at the sub-percent level, on average, and within 1% for most of the FPP acceptance region studied.

To cancel out residual instrumental asymmetries we obtain P_y in $^4\mathrm{He}(e,e'\vec{p})^3\mathrm{H}$ (P_y in Table 1) as the difference of P_y extracted from ^{4}He (P_y(raw) in Table 1) and ^{1}H data. Our systematic studies found the induced polarization thus extracted to be very robust on average and within the acceptance of the detector when binned in various kinematic variables. We reduced the systematic uncertainty on the P_y extraction by a factor of four when compared to previous, similar measurements from E93-049 [1].

In Fig. 1 we show the induced polarization P_y in $^4\mathrm{He}(e,e'\vec{p})^3\mathrm{H}$ extracted from E03-104 (solid circles) together with earlier results from E93-049 [1] (empty circles) and theoretical calculations from the Madrid group [2] (curves and band) which were averaged over the spectrometer acceptance. In the RDWIA, the nuclear current is calculated with relativistic wave functions for the initial bound and outgoing proton. The nuclear current operator can be of *cc1* or *cc2* forms [11] depending on the prescription used to enforce current conservation. The final outgoing proton wave function is a solution of a Dirac equation with global optical potentials to account for FSIs. The optical potential models used are McNeil-Ray-Wallace (MRW) [12] and Love-Franey (RLF) [13]. In Fig. 1 the green band represents the Madrid calculation when MRW is used and the width of the band depends on the form of the nuclear current operator, *cc1* or *cc2*, with *cc1* giving a larger P_y in absolute value. The blue solid and dashed curves represent the Madrid cal-

TABLE I: The induced polarization P_y from E03-104. P_y(raw) is the experimental value of the induced polarization in ${}^4\mathrm{He}(e,e'\vec{p})^3\mathrm{H}$. P_y is the difference between the experimental values of P_y in ${}^4\mathrm{He}(e,e'\vec{p})^3\mathrm{H}$ and ${}^1\mathrm{H}(e,e'\vec{p})$ which gives, in the absence of the induced polarization in ^{1}H, the induced polarization in ^{4}He. Stat. and syst. represent the statistical and systematic uncertainties, respectively.

Q^2 $(\mathrm{GeV}/c)^2$	P_y(raw)	stat.	P_y	stat.	syst.
0.8	-0.0366	0.0042	-0.0415	0.0050	0.0050
1.3	-0.0394	0.0039	-0.0373	0.0043	0.0058

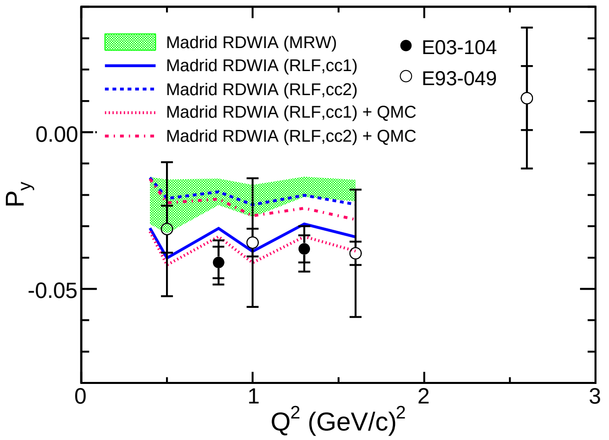

FIG. 1: (Color online) The induced polarization P_y in ${}^4\mathrm{He}(e,e'\vec{p})^3\mathrm{H}$ as a function of Q^2 from E03-104 (solid circles) and E93-049 (empty circles) [1]. The inner and outer error bars represent the statistical and total uncertainties, respectively. The green band displays the Madrid calculation [2] when using MRW as optical potential and *cc1* or *cc2* for the form of the nuclear current operator. For the solid and dashed curves RLF was used with *cc1* (solid) and *cc2* (dashed). The dashed-dotted and dotted curves were obtained from the dashed and solid ones, respectively, by including medium-modified form factors via the QMC model [6]. Lines connect the acceptance-averaged theory calculations.

culation when using the RLF optical potential and *cc1* (solid) or *cc2* (dashed). The considerably reduced systematic uncertainties of the new results make possible a clear distinction between various theoretical prescriptions: the best description of the data is given by RDWIA (RLF,*cc1*). The inclusion of medium-modified form factors via the QMC model [6] slightly increases P_y, in absolute value, more so at large Q^2, as shown by the dashed-dotted and dotted curves.

In Fig. 2 we present the distribution of the induced polarization P_y as function of the missing momentum p_m. Our results are compared to the Madrid RDWIA calculation [2]. Overall, there is good agreement between data and the theoretical prediction. Both data and calculation show an increase in P_y (in absolute value) with increasing p_m. The calculation predicts a stronger variation of P_y in the range of p_m from -0.15 GeV/c to 0 GeV/c compared to 0 GeV/c to 0.15 GeV/c. Although there is some hint in the data that supports this behavior, especially at Q^2 = 0.8 (GeV/c)^2, the size of the statistical uncertainties preclude any definite conclusion.

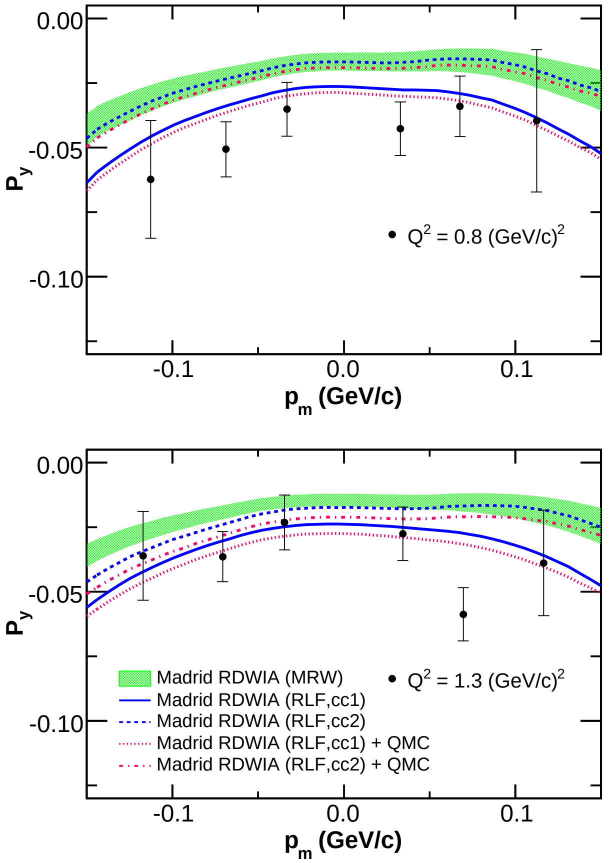

FIG. 2: (Color online) P_y in ${}^4\mathrm{He}(e,e'\vec{p})^3\mathrm{H}$ as a function of missing momentum p_m from E03-104 (solid circles). Also shown are calculations from the Madrid group [2] (notations as in Fig. 1).

In Fig. 3 our P_y results are also compared to the calculation of Schiavilla *et al.* [3]. To facilitate this comparison our data have been corrected for the spectrometer acceptance as this theoretical calculation is only available at $p_m \approx 0$. This correction was determined using the Madrid RDWIA (RLF,cc1) model because it offers a very good qualitative description of the P_y dependence on p_m. The stability of the acceptance correction was

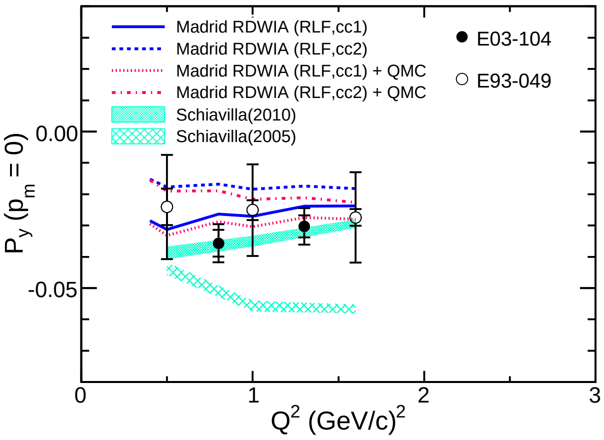

FIG. 3: (Color online) The induced polarization P_y in ^{4}He$(e, e'\vec{p})^3$H as a function of Q^2 extrapolated at missing momentum $p_m \approx 0$ from E03-104 (solid circles) and E93-049 (empty circles) [1]. The inner and outer error bars represent the statistical and total uncertainties, respectively. Calculations from the Madrid group [2] (continuous and dashed curves) and from Schiavilla *et al.* [3, 14] (bands) are also shown.

studied by using other prescriptions within the Madrid RDWIA calculation and the variations were negligible when compared to the experimental uncertainties. The acceptance correction for this experiment was found to be no larger than 20% but cannot be neglected for a consistent comparison. The calculation from the Madrid group is also shown at $p_m \approx 0$. The computation of Schiavilla *et al.* uses variational wave functions for the bound three- and four-nucleon systems, non-relativistic MEC (2-body currents) and free nucleon form factors. The FSIs are treated within the optical potential framework and include both spin-independent and spin-dependent charge-exchange terms which play a crucial role in the prediction of P_y [3] for this calculation. The spin-independent charge-exchange term is constrained by $p + {}^3\text{H} \rightarrow n + {}^3\text{He}$ charge-exchange cross section data while the spin-dependent one is largely unconstrained [3].

Two versions of Schiavilla *et al.* calculation are shown in Fig. 3. The 2005 calculation [3] over-predicts, in absolute value, our measurements of P_y, especially at larger Q^2 but offers a good description of the polarization transfer double ratio [4]. A new 2010 calculation [14] uses our P_y results as additional constraints for the modeling of the charge-exchange terms. The calculation proved insensitive to variations of the spin-dependent charge-exchange term (especially at larger Q^2) and this remains largely unconstrained [14]. However, the spin-independent charge-exchange contribution has been modified to provide a good fit to our data. It remains to be verified whether the agreement with the charge-exchange cross section data from $p + {}^3\text{H} \rightarrow n + {}^3\text{He}$ is still maintained. This 2010 version of the calculation is in good agreement with the polarization-transfer double ratio.

Recently, the Madrid group also made an estimation of the P_y sensitivity to charge-exchange processes within the RDWIA framework. They concluded that P_y in ^{4}He$(e, e'\vec{p})^3$H is unaffected by these processes to a large degree and thus it cannot be used to claim nor asses the size of the charge-exchange contribution in the RDWIA calculation. On the other hand, the charge-exchange cross sections as predicted by the Madrid RDWIA calculation need to be gauged against data.

The role of the charge exchange in ^{4}He$(e, e'\vec{p})^3$H still needs to be clarified. P_y in Schiavilla's 2010 calculation [14] proves to be mostly sensitive to the charge-exchange spin-independent term, leaving the spin-dependent one still largely unconstrained; the Madrid group deems P_y largely insensitive to both terms within the RDWIA frame work. Possibly, a comparison of the induced polarization in ^{4}He$(e, e'\vec{p})^3$H and ^{4}He$(e, e'\vec{n})^3$He could cast some light on the role of charge exchange in this reaction.

Our results for the induced polarization in ^{4}He$(e, e'\vec{p})^3$H combined with those of the polarization-transfer double ratio recently published from this experiment [4] show that a good description of both quantities is attained within the RDWIA frame work with the inclusion of medium modified form-factors via the QMC model, the contribution of the latter being particularly important for the description of the polarization-transfer double ratio. Alternatively, a good description of both quantities is given by the 2010 version of the Schiavilla *et al.* calculation [14] which uses free nucleon form-factors but has important contributions from charge-exchange processes, with the spin-independent charge-exchange term constrained by our induced polarization data.

To summarize, we measured with unprecedented precision the induced polarization P_y in ^{4}He$(e, e'\vec{p})^3$H at $Q^2 = 0.8$ (GeV$/c)^2$ and 1.3 (GeV$/c)^2$. For the first time the systematic uncertainties on this observable were reduced to a size comparable to the statistical uncertainties. We compared our results with theoretical calculations from the Madrid group [2] and Schiavilla *et al.* [3, 14]. The Madrid RDWIA prediction describes well our data when RLF is used as optical potential and $cc1$ as form for the nuclear current operator. The inclusion of medium modified form factors via the QMC model [6] brings this calculation even closer to our results. The 2005 prediction from Schiavilla *et al.* overestimates our P_y results (in absolute value) but gives a good description of the polarization-transfer double ratio [4]. Our data have been used to constrain the charge-exchange spin-independent term in the calculation and this 2010 version describes well both the induced polarization and the polarization transfer double ratio. In examining the question of medium modification, it is important to determine if the modified charge-exchange spin-independent potential used in the 2010 calculation is compatible with existing data, and to look for additional ways to constrain both the charge-exchange spin-dependent and spin-independent terms.

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