

## Precise Extraction of the Induced Polarization in the ${}^4\text{He}(e, e'\vec{p}){}^3\text{H}$ Reaction

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We measured with unprecedented precision the induced polarization  $P_y$  in  ${}^4\text{He}(e, e'\vec{p}){}^3\text{H}$  at  $Q^2 = 0.8$  and  $1.3$   $(\text{GeV}/c)^2$ . 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 overestimated 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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Why and to what extent the nucleon changes its structure while embedded in nuclear medium has been a long-standing 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,  $(P'_x/P'_z)_{\text{He}}/(P'_x/P'_z)_{\text{H}}$  extracted from measurements of the polarization-transfer coefficients,  $P'_x$  and  $P'_z$ , in elastic  $\vec{e}p$  scattering and quasielastic scattering on  ${}^4\text{He}$  [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  ${}^4\text{He}$  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, 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, an interpretation of a small quenching in the polarization-transfer double ratio as evidence of unconventional nuclear effects requires excellent control of conventional reaction mechanisms and hence remains, to some degree, model dependent. The induced polarization  $P_y$ , experimentally accessible 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  ${}^4\text{He}(e, e'\vec{p}){}^3\text{H}$ , and this Letter presents the results.

We report measurements of the induced polarization  $P_y$  in the quasielastic reaction  ${}^4\text{He}(e, e'\vec{p}){}^3\text{H}$ , at four-momentum transfer  $Q^2$  of 0.8 and 1.3  $(\text{GeV}/c)^2$  and missing momentum,  $p_m$  ranging from 0 to 160  $\text{MeV}/c$ . A longitudinally polarized electron beam with flipping polarization direction and a current of 80  $\mu\text{A}$  was incident on  ${}^4\text{He}$  and  ${}^1\text{H}$  targets, and the scattered electron and recoil proton were detected in coincidence in two high-resolution spectrometer arms. The  ${}^4\text{He}$  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  ${}^1\text{H}(\vec{e}, e'\vec{p})$  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  ${}^4\text{He}(\vec{e}, e'\vec{p}){}^3\text{H}$  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  ${}^1\text{H}$  data have been used to check for the presence of instrumental asymmetries. In the one-photon-exchange approximation  $P_y$  in  ${}^1\text{H}(e, e'\vec{p})$  is expected to be zero. The two-photon-exchange processes could yield a nonzero 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. As a result, we see only small variations, at the subpercent level, in the experimental azimuthal asymmetries for  ${}^1\text{H}(e, e'\vec{p})$ , with few outliers up to 1% in the few inefficient regions and at the edges of the FPP acceptance. On average, the experimental azimuthal asymmetries for  ${}^1\text{H}(e, e'\vec{p})$  are at the subpercent level.

To cancel out these residual instrumental asymmetries, we obtain  $P_y$  in  ${}^4\text{He}(e, e'\vec{p}){}^3\text{H}$ ,  $P_y$  in Table I, as the difference of  $P_y$  extracted from  ${}^4\text{He}$ ,  $P_y(\text{raw})$  in Table I, and  ${}^1\text{H}$  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 4 when compared to previous, similar measurements from

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

$Q^2$ ( $\text{GeV}/c)^2$	$P_y(\text{raw})$	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

E93-049 [1]. Our data are used to put to stringent test state-of-the-art theoretical calculations, and such comparisons are presented in what follows.

In Fig. 1 we show the induced polarization  $P_y$  in  ${}^4\text{He}(e, e'\bar{p}){}^3\text{H}$  extracted from E03-104 (upper panel) together with earlier results from E93-049 [1] (lower panel) 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

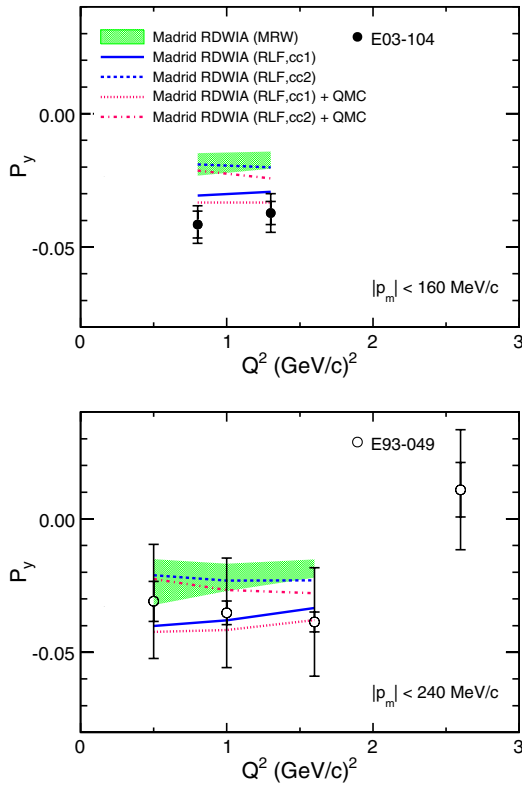


FIG. 1 (color online). The acceptance-averaged induced polarization  $P_y$  in  ${}^4\text{He}(e, e'\bar{p}){}^3\text{H}$  as a function of  $Q^2$  from E03-104 (upper panel) and E93-049 (lower panel) [1]. The inner and outer error bars represent the statistical and total uncertainties, respectively. 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 dash-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.

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 calculation when using the RLF optical potential and  $cc1$  (solid line) or  $cc2$  (dashed line). The older E93-049 experiment [1] averaged over a larger range in missing momentum than E03-104, see Fig. 1, and  $P_y$  is predicted to increase, in absolute value, with increasing missing momentum. This causes the apparent drop in the theory results at the kinematics of E93-049 when compared to those of E03-104. 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 dash-dotted and dotted curves.

In Fig. 2 we present the distribution of the induced polarization  $P_y$  as a 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

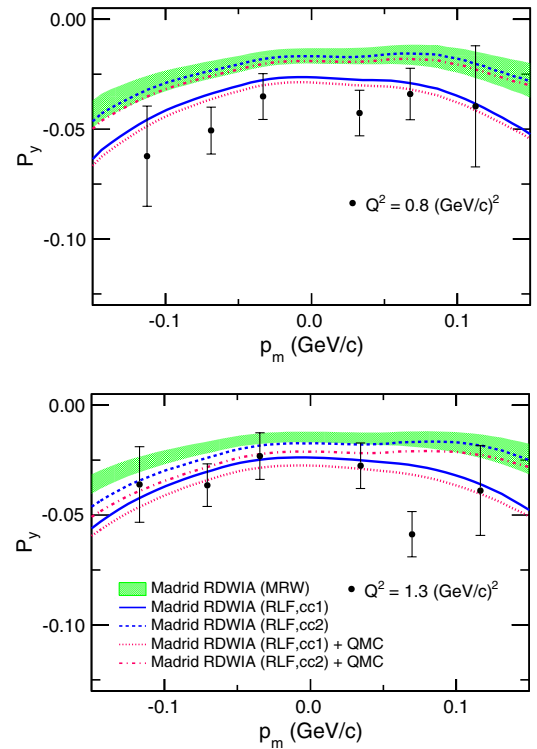


FIG. 2 (color online).  $P_y$  in  ${}^4\text{He}(e, e'\bar{p}){}^3\text{H}$  as a function of missing momentum  $p_m$  from E03-104 (solid circles). Also shown are calculations from the Madrid group [2] (notations as in Fig. 1).

increasing  $p_m$ . The calculation predicts a stronger variation of  $P_y$  in the range of  $p_m$  from  $-0.15$  to  $0$  GeV/ $c$  compared to  $0$  to  $0.15$  GeV/ $c$ . Although there is some hint in the data that supports this behavior, especially at  $Q^2 = 0.8$  (GeV/ $c$ )<sup>2</sup>, the size of the statistical uncertainties precludes any definite conclusion.

Another state-of-the-art theoretical calculation is the computation of Schiavilla *et al.* which uses variational wave functions for the bound three- and four-nucleon systems, nonrelativistic meson-exchange currents (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].

In Fig. 3 our  $P_y$  results are 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 ( $< 20\%$  for this experiment) 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 studied by using other prescriptions within the Madrid RDWIA calculation, and the variations were negligible when compared to the experimental uncertainties. The calculation from the Madrid group is also shown at  $p_m \approx 0$ . The remaining small but visible variation in the induced polarization between E93-049 and E03-104 kinematics is due to the higher beam energies used in E93-049. Although the prediction of Schiavilla *et al.*, Schiavilla (2005) in Fig. 3, offers a good description of the

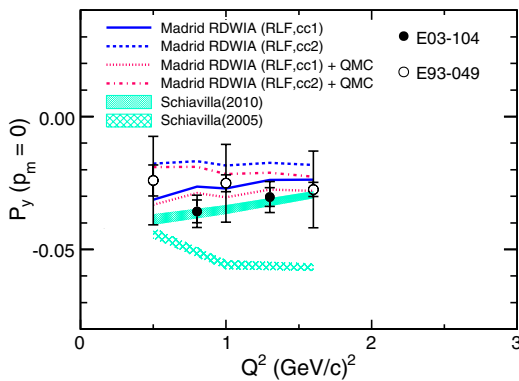


FIG. 3 (color online). The induced polarization  $P_y$  in  ${}^4\text{He}(e, e'\bar{p}){}^3\text{H}$  as a function of  $Q^2$  extrapolated at missing momentum  $p_m \approx 0$  from E03-104 (solid circles) and E93-049 (empty circles) [1]. The inner and outer error bars represent the statistical and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

polarization-transfer double ratio [4], it overpredicts, in absolute value, our measurements of  $P_y$ , especially at larger  $Q^2$ . This evident discrepancy prompted a revision of this calculation. The new calculation [14], Schiavilla (2010) in Fig. 3, 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 also in good agreement with the polarization-transfer double ratio.

The role of the charge exchange in  ${}^4\text{He}(e, e'\bar{p}){}^3\text{H}$  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 unconstrained; the Madrid group deems  $P_y$  largely insensitive to both terms within the RDWIA framework. On the other hand, the charge-exchange cross sections as predicted by the Madrid RDWIA calculation need to be gauged against data. Possibly, a comparison of the induced polarization in  ${}^4\text{He}(e, e'\bar{p}){}^3\text{H}$  and  ${}^4\text{He}(e, e'\bar{n}){}^3\text{He}$  could cast some light on the role of charge exchange in this reaction.

To summarize, we measured with unprecedented precision the induced polarization  $P_y$  in  ${}^4\text{He}(e, e'\bar{p}){}^3\text{H}$  at  $Q^2 = 0.8$  and  $1.3$  (GeV/ $c$ )<sup>2</sup>. 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 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 induced polarization data have then 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. Our high-precision data point to the need to carefully consider both the charge-exchange spin-independent and spin-dependent terms in realistic calculations, to settle the extent of medium modifications in nucleon structure.

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