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ABSTRACT

We report the measurement of the ratio of polarization-transfer components, P_x/P_z, in the $^2\mathrm{H}(\vec{e},e'\vec{p})n$ reaction at low and high missing momenta, in search of differences between free and bound protons. The observed deviation of P_x/P_z from that of a free proton, which is similar to that observed in ^{4}He, indicates that the effect in nuclei is a function of the virtuality of the knock-out proton and the missing momentum direction, but not the average nuclear density. There is a general agreement between the data and calculations, which assume free proton form factors, however, the measurements are consistently about 10% higher.

Scattering polarized electrons off protons and simultaneous measurement of two polarization-transfer components allow one to determine the ratio of the elastic electric to magnetic form factors (FFs) [1,2]. This method reduces many potential sources of systematic uncertainties and enables high-precision measurements of this ratio.

In nuclei, the effects of the strong nuclear field on a bound nucleon are an interesting issue: Do bound nucleons have the same properties as free ones [3]? Medium modification of the bound-nucleon structure may affect the nucleon FFs. Thus, measurements of the ratio of the polarization components of a proton which was knocked-out by a polarized electron (in quasi-free scattering) is a good tool for detecting changes in the bound-proton structure reflected in the FF ratio. The polarization transfer in the $^4\mathrm{He}(\vec{e},e'\vec{p})$ reaction was measured, and observed deviations from a calculation with free proton FFs were attributed to nuclear medium modifications [4,5]. However, it is not clear what mainly causes these changes: Is it the nuclear density? Or are they due to the nucleon being off-shell in the nuclear medium? It is particularly interesting to measure such effects in the deuteron, which is the most weakly bound nuclear system (frequently used as a 'free-neutron' target). Changes in the 'off-the-mass-shell' nucleons may be evident even in the deuteron.

We report here measurements of the transverse and longitudinal polarization-transfer components of the knocked out proton in the quasi-free $^2\mathrm{H}(\vec{e},e'\vec{p})n$ reaction as a function of the proton

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missing-momentum (p_{miss}). We parametrize the *'off-shellness'* using the proton virtuality, defined as:

$$\nu \equiv \left(M_A - \sqrt{M_{A-1}^2 + |\vec{p}|_{\text{miss}}^2}\right)^2 - |\vec{p}|_{\text{miss}}^2 - M_p^2, \tag{1}$$

where M_A, M_{A-1}, and M_p are the target, residual nucleus, and proton masses, respectively, and $\vec{p}_{\text{miss}} = \vec{q} - \vec{p}_p$ where $\vec{q}$ is the momentum transfer and $\vec{p}_p$ is the out-going proton momentum. We also define the missing energy, E_{miss} and four-momentum P_{miss} as $E_{\text{miss}} = q_0 - E_p$ and $P_{\text{miss}}^2 = E_{\text{miss}}^2 - \vec{p}_{\text{miss}}^2$ (where q_0 is the energy transfer and E_p the outgoing proton energy). Indeed, there is no unique way to define *'off-shellness'*. Equation (1) assumes that only the struck proton is off-shell ($\nu = P_{miss}^2 - M_p^2 \neq 0$) to conserve energy and momentum at the reaction vertex (the residual system is on-shell). This definition of ν can be applied to both ^{2}H and ^{4}He (as well as to heavier nuclei).

We study the deviations of the measured bound-proton polarization transfer ratios from those of the free proton [6]. The data are compared to previous measurements on the deuteron [7], obtained at high momentum transfer, and ^{4}He [4,5]. The new data extend significantly the previously covered virtuality ranges. As shown below, with this choice of virtuality, ν (eq. (1)), the measured deviations from the free proton are the same for the deuteron and ^{4}He and exhibit a smooth behavior as a function of ν. We compare the measurements also to state of the art calculations of the deuteron which use free nucleon FFs and take into account meson exchange currents (MEC), isobar configurations (IC), relativistic corrections (RC), and final-state interactions (FSI) [8].

In the elastic $^1\text{H}(\vec{e}, e'\vec{p})$ reaction there are two beam helicity dependent, non-vanishing, polarization-transfer components: transverse, P_x (perpendicular to the proton momentum in the scattering plane defined by the incident and scattered electron), and longitudinal, P_z (along the proton momentum). In the one photon exchange approximation their ratio $(P_x/P_z)_{\text{H}}$ is directly related to the ratio of the elastic electric $G_E^p(Q^2)$ to the magnetic $G_M^p(Q^2)$ FFs at a given four-momentum transfer Q^2 [2]:

$$\left(\frac{P_x}{P_z}\right)_{\text{H}} = -\frac{2M_p}{(E+E')\tan(\theta_e/2)} \cdot \frac{G_E^p(Q^2)}{G_M^p(Q^2)}, \tag{2}$$

where E (E') is the incident (scattered) electron energy, and θ_e is the electron scattering angle.

For quasi-free elastic scattering off a bound nucleon, the knock-out proton is in general not ejected in the momentum-transfer ($\vec{q}$) direction (and in the scattering plane) due to its initial momentum. This introduces an additional plane, the reaction plane, determined by the momentum transfer ($\vec{q}$) and the outgoing proton momentum ($\vec{p}_p$), characterized by the spherical angles θ_{pq} and ϕ_{pq} as shown in Fig. 1. The incident and scattered electron momenta are indicated by $\vec{k}$ and $\vec{k}'$, and $\vec{q}$ is the momentum transfer. The initial and outgoing proton momenta are indicated by $\vec{p}_i$ and $\vec{p}_p$, respectively. With no final state interactions $\vec{p}_i = -\vec{p}_{\text{miss}}$, and $\vec{p}_p$ is the detected proton momentum. Following the convention of [5] the polarization components reported here are the ones in the scattering plane along (z) and perpendicular (x) to $\vec{q}$.

The experiment was performed at the Mainz Microtron (MAMI) using the A1 beam-line and spectrometers [9]. For the measurements, 600 and 630 MeV CW polarized electron beams of 10 μA current were used. The average beam polarization was 80%, measured with a Møller polarimeter. The beam helicity was flipped at a rate of 1 Hz. The target consisted of an oblong shaped cell (50 mm long, 11.5 mm diameter) filled with liquid deuterium. Two high-resolution, small solid-angle spectrometers with momentum acceptances of 20–25% were used to detect the scattered electrons and knocked out protons in coincidence. The proton spectrometer was equipped with a focal-plane polarimeter (FPP) with a 3–7 cm thick carbon analyzer [9,10]. The spin dependent scattering of the polarized proton by the carbon analyzer allows the determination of the proton longitudinal and transverse polarization components at the reaction point in the target [10]. These polarization-transfer components were obtained by correcting for the spin precession (∼ 100°, close to the 90° optimum) in the spectrometer magnetic field.

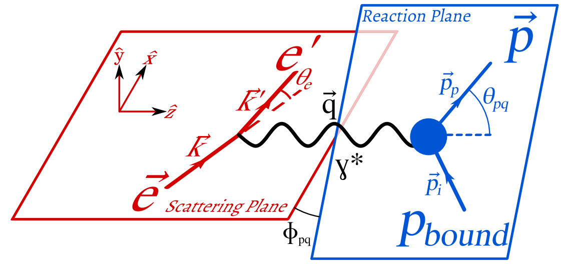

Fig. 1. The kinematics for quasi-elastic scattering of a bound proton in a nucleus, defining scattering and reaction planes.

The measurements were performed in four kinematic set-ups that covered two Q^2 ranges and two missing-momentum ranges each. Details of the kinematic settings are summarized in Table 1, where p_p and θ_p (p_e and θ_e) are the knock-out proton (scattered electron) momentum and angle. The missing momentum is taken to be positive (negative) if a component of $\vec{p}_{\text{miss}}$ is parallel (anti-parallel) to the momentum-transfer vector ($\vec{q}$). Also shown are the ranges of the extracted angle between $\vec{q}$ and -$\vec{p}_{\text{miss}}(\theta_{pmq})$.

In the analysis, cuts were applied to identify coincident electrons and protons that originate from the deuterium target, and to ensure good reconstruction of tracks in the spectrometer and FPP. Only events that scatter by more than 10° in the FPP were selected (to remove Coulomb scattering events).

Helicity-independent corrections to the measured ratios (acceptance, detector efficiency, target density, etc.) are largely canceled out by the frequent flips of the beam helicity. The uncertainties in the beam polarization, carbon analyzing power, and efficiency are reduced well below the statistical uncertainty by taking the P_x/P_z ratio.

The total systematic error in the P_x/P_z ratio is estimated to be about 2% and is due mainly to the reaction vertex reconstruction (which dominates both the polarization and the missing-momentum resolutions) and the spin-precession evaluation (that impacts only the polarization).

The data for both Q^2 setups are presented in Fig. 2 as a function of the missing-momentum. The data are compared to a calculation of P_x/P_z for the deuteron [8] that takes into account FSI, MEC, IC, and RC. The calculations presented here (and the hydrogen values used below) use the free proton FFs of Bernauer et al. [6]. The theoretical results shown in Fig. 2 were obtained by averaging calculations event-by-event over the entire data sample in each bin. The observed large difference between the low and high Q^2 data at the same missing momenta shown in Fig. 2 is mainly a reflection of the different kinematical parameters. These are removed by dividing the polarization ratio by that of hydrogen (Eq. (2)), which also factors out possible differences in the free form factor ratio and enables a direct comparison to previous measurements (on the deuteron and ^{4}He).

Fig. 3 shows the double-ratio of the deuteron data to hydrogen, $(P_x/P_z)_{^2\text{H}}/(P_x/P_z)_{\text{H}}$, as a function of the virtuality. The data are shown separately for positive and negative missing momenta to show a possible dependence (as suggested by the calculation, see Fig. 4).

Table 1
The kinematic settings in the experiment. The angles and momenta represent the center values for the two spectrometer set-ups. Also shown is the range of $\theta_{p_m q}$, the angle between $\vec{q}$ and $-\vec{p}_{\text{miss}}$.

Kinematic		Setup			
		A	B	C	D
E_{beam}	[MeV]	600	600	630	630
Q^2	[GeV^2]	0.40	0.40	0.18	0.18
p_{miss}	[MeV]	−80 to 75	75 to 175	−80 to −15	−220 to −130
$E_{e'}$	[MeV]	384	463	509	398
$\theta_{e'}$	[deg]	82.4	73.8	43.4	49.4
p_p	[MeV]	668	495	484	665
θ_p	[deg]	−34.7	−43.3	−53.3	−39.1
$\theta_{p_m q}$	[deg]	0 to 180	140 to 180	0 to 140	0 to 45
# of events after cuts		213,525	172,142	2,383,909	790,365

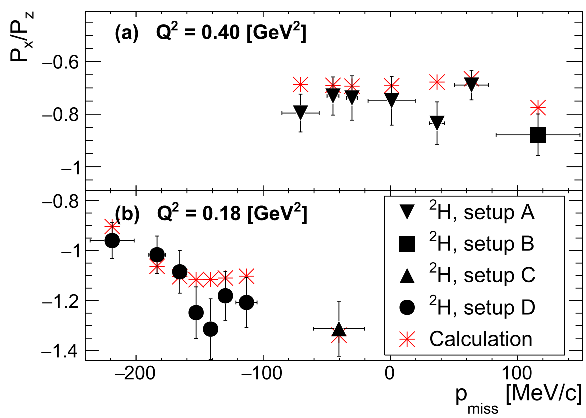

Fig. 2. The measured ratio of helicity dependent polarization components, P_x/P_z, versus the missing-momentum. The data are compared to the calculation based on the theoretical framework of Ref. [8]. The uncertainties are statistical only, and the horizontal bars indicate the p_{miss} standard deviation in each bin.

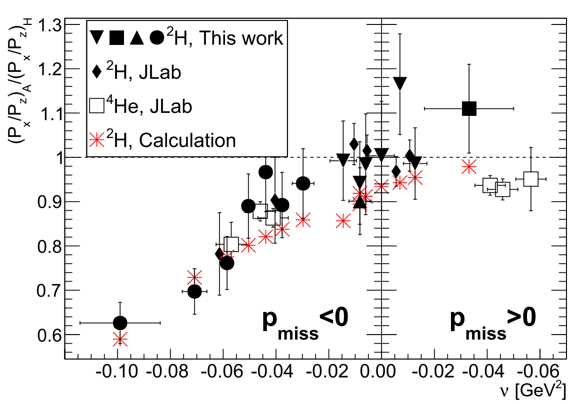

Fig. 3. The measured double-ratio $(P_x/P_z)_A/(P_x/P_z)_{\text{H}}$ ($A = {}^2\text{H}, {}^4\text{He}$) as a function of the proton virtuality, ν, for deuteron (this work and [7]) and for ^{4}He [5]. The JLAB deuteron data are for $Q^2 = 1$ GeV^2 and the ^{4}He data are for $Q^2 = 0.8$ GeV^2. The virtuality dependence is shown separately for positive and negative missing momenta. The symbols for the data of this work correspond to those in Fig. 2. Also shown is a calculation for the deuteron (see text for details).

Our data are supplemented with higher Q^2 deuteron data measured at Jefferson Lab [7]. Our new measurements double the virtuality range covered by the previous experiments. Within the overlap, the data are in good agreement. The comparison with the higher-momentum data of JLab (up to $Q^2 = 1$ GeV^2) suggests essentially no Q^2 dependence.

The deuteron double-ratio data are compared with those of proton knock-out from ^{4}He measured at JLab [5]. The deuteron is the least bound nucleus in nature with the largest average distance between the nucleons and thus the lowest nuclear average density. On the other hand ^{4}He is a very strongly-bound nucleus with a very high average density.

The excellent agreement between the deuteron and ^{4}He data, with the same behavior of the double ratio $(P_x/P_z)_A/(P_x/P_z)_{\text{H}}$ shown in Fig. 3, suggests that the deviations from the free proton value due to nuclear effects do not depend on the nuclear average density. It is rather the virtuality, and the direction of the missing momentum, that determine the double-ratio behavior. The nuclear density would affect the number of protons of a given virtuality (i.e. a given 'off-shellness') in the nucleus.

The new data reported here allow a meaningful comparison to calculations [8], which include medium effects but assume *unmodified* FFs for the proton in the deuteron. The calculations show (see Fig. 3) a clear virtuality dependence of the ratio $(P_x/P_z)_{^2\text{H}}$ to that of the free proton which depends on the sign of the missing momentum. The contributions of the different corrections in the calculation are shown in Fig. 4.

The calculations in [8] were performed non-relativistically (NR), with relativistic corrections of the first order (RC), including meson exchange currents (MEC), with isobar contribution (IC), and with final state interaction (FSI). For simplicity, Figs. 2 and 3 present only the full calculations, with all the above included. The virtuality dependence is mostly due to FSI, and MEC and IC contribute little to the major effect. This can be seen clearly in Fig. 4. The plane wave model (PWBA) accounts for a reduction of about 10% in the polarization ratio, while the distorted wave calculations (DWIA) and the data are lower by about 50% over the same range. Including relativistic corrections of the first order in the calculations, improves the agreement with the data but does not change the slope of the plotted ratio as a function of virtuality.

The general agreement between the data and the calculations (Fig. 3) suggests that the deviations from a free proton are mainly due to the proton motion and the FSI in the deuteron. However, consistent deviations between the data and the calculations exist. The data are 10% above the calculation resulting in a significant difference of 4 standard deviations. These deviations have no systematic dependence on either the virtuality or the angle between $\vec{p}_{\text{miss}}$ and $\vec{q}$ (see the figures in the supplemental material [11]). The uncertainty in the calculations, assessed by changing the N–N potential from AV18 to Bonn ($\sim 2\%$) or the FF parametrization (essentially no effect), is well below this deviation over the measured region. This may suggest that additional corrections, such as modifications in the bound nucleon structure may still be required.

We note that the deuteron data are above the calculation while the ^{4}He data are 5–8% below their calculations (both using free FFs). Since the calculations for ^{4}He are not the same as those for the deuteron, the deviations may be due to different effects. However, if the reason is modifications in the bound nucleon structure, these corrections should increase the theoretical predictions for the deuteron and decrease them for ^{4}He.

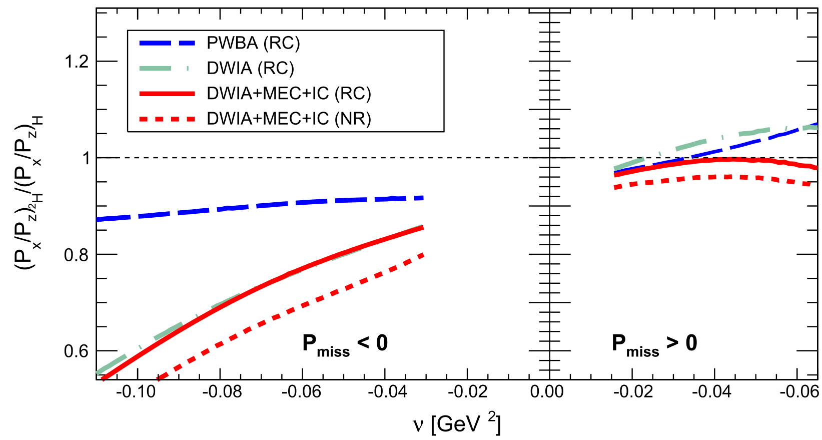

Fig. 4. Theoretical results of [8] with FSI (DWIA) and without (PWBA), with first order relativistic corrections (RC), and without it (NR). Also shown is the effect of adding MEC+IC corrections.

The theoretical results are different for positive and negative p_{miss} kinematics. Calculations [8] extended to a larger positive missing momentum range than the data even strengthen this claim (see Fig. 4). This may be observed also in the ^{4}He data [5]. This trend in the calculation is predominantly associated with different FSI in the two kinematics and should be confirmed for the deuteron with additional data at larger positive p_{miss}.

To summarize, the new data of the polarization-transfer double-ratios $(P_x/P_z)_{^2\mathrm{H}}/(P_x/P_z)_{\mathrm{H}}$ extend the previous measurements and almost double the virtuality range. The measurements agree well with the previous ^{2}H and ^{4}He data sets (obtained in different kinematics). The question of medium modification is rather involved and may depend on several parameters. Our data add several significant pieces to this puzzle. They clearly show that the virtuality is an important parameter to describe the measured $(P_x/P_z)_{^2\mathrm{H}}$ and that the data are nearly independent of the average nuclear density and Q^2. However, taking the form factors for a bound proton to be those of a free proton, the calculations do not fully reproduce the strong virtuality dependence observed in our measurement. This may indicate the need to invoke in-medium form factor modifications. These results suggest to further extend the measurements on the deuteron in the positive p_{miss} sector, as well as extending both the ^{4}He and deuteron data to larger virtuality. Indeed, such measurements were proposed [12] and approved at JLAB.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.physletb.2017.01.034.

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