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Measurement of polarization-transfer to bound protons in carbon and its virtuality dependence

A1 Collaboration

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ABSTRACT

We measured the ratio P_x/P_z of the transverse to longitudinal components of polarization transferred from electrons to bound protons in ^{12}C by the $^{12}\mathrm{C}(\vec{e},e'\vec{p})$ process at the Mainz Microtron (MAMI). We observed consistent deviations from unity of this ratio normalized to the free-proton ratio, $(P_x/P_z)_{^{12}\mathrm{C}}/(P_x/P_z)_{^{1}\mathrm{H}}$, for both s- and p-shell knocked out protons, even though they are embedded in averaged local densities that differ by about a factor of two. The dependence of the double ratio on proton virtuality is similar to the one for knocked out protons from ^{2}H and ^{4}He, suggesting a universal behavior. It further implies no dependence on average local nuclear density.

Deviations of quasi-elastic measurements on nuclei from those performed on protons or from calculations using free-proton form-factors (FFs) reflect various many-body effects, potentially including medium modifications of the bound proton structure in the nuclear field [1,2]. The ratio of the transverse (P_x) to longitudinal (P_z) polarization transfer components measured in the elastic double-polarized process $^1\mathrm{H}(\vec{e},e'\vec{p})$ is proportional to the ratio of the electric to magnetic FFs of the free proton, $R_{^1\mathrm{H}} \equiv (P_x/P_z)_{^1\mathrm{H}} \propto G_E^p/G_M^p$ [3]. In nuclei, the ratio of the polarization transfer components to a bound proton, $R_A \equiv (P_x/P_z)_A$, can be determined from the analogous quasi-free proton knock-out process $A\left(\vec{e},e'\vec{p}\right)$. Measurements of R_A eliminate many systematic uncertainties and thus constitute a sensitive and precise tool to study possible deviations of a bound proton properties from a free one.

Previous double polarized proton knock-out experiments on light nuclei, ^{2}H and ^{4}He, were found to be in agreement when compared in terms of the proton virtuality, which is a measure of the "off-shellness" of the bound proton (see Eq. (2)). The measurements showed no dependence on the average nuclear density nor on momentum transfer [4]. For the deuteron, detailed calculations [5] explained the deviations from the free proton by final state interactions (FSI). It is thus interesting to extend the measurements to heavier nuclei were FSI effects are expected to be different.

The ^{12}C nucleus is a particularly appealing target for such studies as one can selectively probe protons from specific nuclear shells, s and p. The average local densities in these shells differ

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Table 1
The kinematic settings in the experiment. The angles and momenta represent the central values for the two spectrometers: p_p and θ_p (p_e and θ_e) are the knocked out proton (scattered electron) momentum and scattering angles, respectively.

Kinematic	Setting	
	A	B
Q^2 [GeV^2/c^2]	0.40	0.18
p_{miss} [MeV/c]	−130 to 100	−250 to −100
p_e [MeV/c]	385	368
θ_e [deg]	82.4	52.9
p_p [MeV/c]	668	665
θ_p [deg]	−34.7	−37.8
# of events after cuts	1.7 M	1.1 M

by about a factor of two, which was predicted to impact the polarization transfer to s- and p-shell protons differently [6]. Previous measurements on s- and p-shell protons in ^{16}O were limited in statistics and the kinematical range covered [7].

In this paper we report on the measurements of the P_x/P_z ratio for protons bound in carbon, $^{12}\mathrm{C}(\vec{e}, e'\vec{p})$, and present the double ratio $R_{^{12}\mathrm{C}}/R_{^1\mathrm{H}}$. In terms of virtuality, our results exhibit consistency between s- and p-shell protons as well as with measurements obtained on other light nuclei. Thus, they confirm the absence of average nuclear density dependence even in the heavier nucleus ^{12}C.

The experiment was performed at the Mainz Microtron (MAMI) accelerator using the A1 beam-line and spectrometers [8]. We used a 600 MeV continuous-wave polarized electron beam with a current of about 10 μA. The average beam polarization was about 80%, measured with a Møller polarimeter and verified by Mott polarimetry. The uncertainty in the beam polarization was less than 5%. The beam helicity was flipped at a rate of 1 Hz. Two high-resolution, small solid-angle spectrometers with momentum acceptances of 20–25 % were used to detect the scattered electrons in coincidence with the knocked-out protons. The target consisted of three carbon foils of 0.8 mm thickness each, separated by about 1.5 cm and tilted at an angle of 40° with respect to the beam. The usage of three tilted foils reduced the proton energy loss in the target and improved the resolution for the reaction-vertex determination. This reduced the systematic uncertainty in the determined polarization transfer components at the reaction point. The proton spectrometer was equipped with a polarimeter placed behind its focal-plane (FPP) using a 7 cm thick carbon analyzer [8,9]. The spin-dependent scattering of the polarized proton by the carbon analyzer enables the determination of the proton transverse polarization components at the focal plane [9]. The polarization-transfer components at the reaction point were obtained by correcting the measured components for the spin precession in the magnetic field of the spectrometer. Following the convention of [2], both P_z and P_x were determined in the scattering plane, defined by the incident and scattered electron momenta, where P_z is along and P_x is perpendicular to the momentum transfer vector, $\vec{q}$.

In the analysis, cuts were applied to identify coincident electrons and protons that originate from the carbon target, and to ensure good reconstruction of tracks in the spectrometers and the FPP. To remove Coulomb scattering events by the carbon analyzer, we selected only events that scattered by more than 8° in the FPP.

The polarization transfer components P_x and P_z were first determined as a function of the proton missing momentum defined as $\vec{p}_{\text{miss}} = \vec{q} - \vec{p}_p$, where $\vec{p}_p$ is the outgoing proton momentum. We define the scalar missing momentum, $p_{\text{miss}} \equiv \pm |\vec{p}_{\text{miss}}|$, where the sign is taken to be positive (negative) if the longitudinal component of $\vec{p}_{\text{miss}}$ is parallel (anti-parallel) to $\vec{q}$. The measurements were performed in two kinematical settings that covered two ranges in p_{miss} and two ranges in the invariant four-momentum

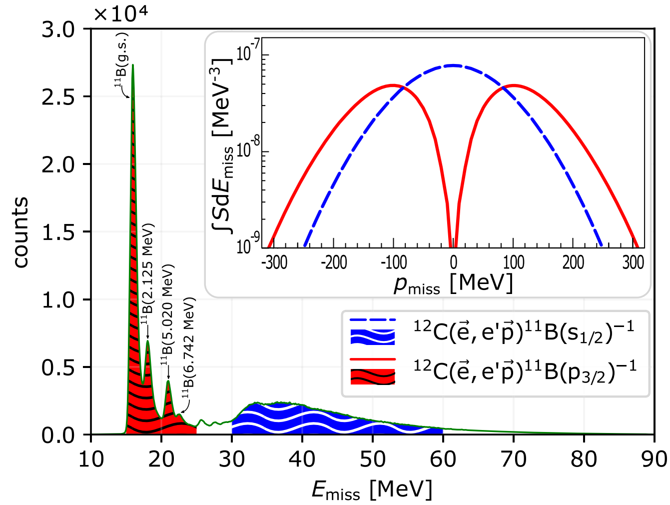

Fig. 1. The proton missing energy spectrum for $^{12}\mathrm{C}(e, e'p)$ in setup A. The distinct peaks correspond to removal of $p_{3/2}$-shell protons in ^{12}C resulting in ^{11}B ground state and excited states as noted. The E_{miss} ranges considered in the analysis for $p_{3/2}$ and $s_{1/2}$ protons are marked in red and blue, respectively (color online). The green line denotes the E_{miss} range used for the analysis combining all protons. The inset shows the momentum distribution predictions of the independent particle shell model for $p_{3/2}$ and $s_{1/2}$ protons in ^{12}C, obtained from [10].

transfer $Q^2 = \vec{q}^2 - \omega^2$, where ω is the energy transfer. Details of the kinematics are summarized in Table 1.

The protons knocked out from the s and p shells were identified by their missing energy. The missing energy is defined as $E_{\text{miss}} \equiv \omega - T_p - T_{^{11}\mathrm{B}}$, where T_p is the measured kinetic energy of the outgoing proton, and $T_{^{11}\mathrm{B}}$ is the calculated kinetic energy of a recoiling ^{11}B nucleus (g.s.). The missing-energy spectrum of setting A is shown in Fig. 1. The sharp peaks correspond to the ground state and the lowest excited states of the recoiling ^{11}B. Following Dutta et al. [10] we present the polarization-transfer results for two ranges of E_{miss} shown in the figure: the first ($15 < E_{\text{miss}} < 25$ MeV) corresponds to proton removal primarily from the ^{12}C $p_{3/2}$ shell; the second ($30 < E_{\text{miss}} < 60$ MeV) corresponds predominantly to proton removal from the s-shell. The missing energy cut allows some s-shell strength in the p-shell region and vice versa. In addition, we show the combined data from the entire E_{miss} range ($10 < E_{\text{miss}} < 90$ MeV) covering proton removal from both s- and p-shells. The inset in Fig. 1 (adapted from [10]), shows the predicted momentum distributions of p- and s-shell protons in ^{12}C obtained from an independent particle shell model spectral function (S) [10]. The difference between the s- and p-shell proton momentum distributions around $p_{\text{miss}} = 0$, may impact the polarization transfer in this region.

Helicity-independent uncertainties in the measured ratios (acceptance, detector efficiency, target density, etc.) largely cancel out due to frequent flips of the beam helicity. The uncertainties in 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 uncertainty in $R_{^{12}\mathrm{C}}$, dominated by the vertex position reconstruction in the target, does not exceed 2% and is about 25% of the statistical uncertainty. In the following figures, only the statistical uncertainties are shown.

The measured helicity-dependent ratios $R_{^{12}\mathrm{C}}$ for both settings are presented in Fig. 2 (top) as a function of p_{miss}. The difference in $R_{^{12}\mathrm{C}}$ between s- and p-shell proton removal with the same p_{miss} is clearly visible in the figure. We removed some contributions to the differences between data at the same p_{miss}, which are due to the different kinematics (or momentum transfer), by dividing $R_{^{12}\mathrm{C}}$ by the hydrogen ratio