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Components of polarization-transfer to a bound proton in a deuteron measured by quasi-elastic electron scattering

A1 Collaboration

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ABSTRACT

We report the first measurements of the transverse (P_x and P_y) and longitudinal (P_z) components of the polarization transfer to a bound proton in the deuteron via the $^2\mathrm{H}(\vec{e}, e'\vec{p})$ reaction, over a wide range of missing momentum. A precise determination of the electron beam polarization reduces the systematic uncertainties on the individual components to a level that enables a detailed comparison to a state-of-the-art calculation of the deuteron using free-proton electromagnetic form factors. We observe very good agreement between the measured and the calculated P_x/P_z ratios, but deviations of the individual components. Our results cannot be explained by medium modified electromagnetic form factors. They point to an incomplete description of the nuclear reaction mechanism in the calculation.

Measurements of the polarization transfer $\vec{P} = (P_x, P_y, P_z)$ from a polarized electron to a bound nucleon by the $A(\vec{e}, e'\vec{p})$ reaction and their comparison to those of a free proton were suggested as a powerful tool to observe modifications in the bound proton structure [1]. These require detailed calculations incorporating nuclear effects and overcoming a difficulty of separating nuclear effects from internal nucleon structure changes. Measurements on ^{4}He compared to relativistic distorted-wave calculations were claimed to favor medium-modified proton form factors or spin-dependent charge-exchange final-state interaction [2–4].

The deuteron (^{2}H) is the simplest nuclear system, with two loosely bound nucleons. Even though it is often used as a 'free neutron' target, measurements on the bound proton in ^{2}H in quasi-elastic kinematics are known to have marked differences in comparison to those on a free proton [5]. Such differences can be ascribed to final state interactions (FSI) and other nuclear effects in the deuteron like meson exchange currents (MEC) and isobar configurations (IC), as well as to nuclear medium modifications of the bound proton electromagnetic form factors (FFs). Since most of the properties of the deuteron are described very well by calculations, it serves also as a benchmark for nuclear theory. As such it is

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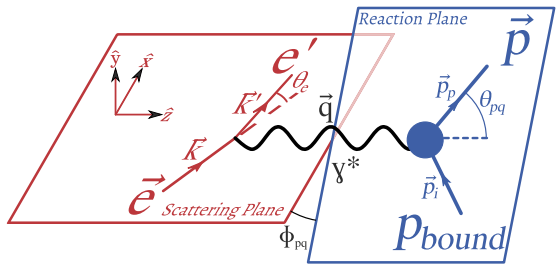

Fig. 1. The kinematics for quasi-elastic scattering of a bound proton in a nucleus, defining the scattering and reaction planes.

important to establish that present state-of-the-art calculations indeed provide a correct description of the deuteron. Thus, new high precision polarization transfer data can add important information to further test and improve the calculations, since polarization observables generally provide more sensitive tests.

Measurements of the ratio of the polarization transfer components P_x to P_z (P_x/P_z) to a bound proton in ^{2}H$(\vec{e}, e'\vec{p})$ over a wide region of the proton missing momentum were reported in [6]. Measuring the ratio, instead of the individual components, eliminates many systematic experimental uncertainties, particularly those due to electron beam polarization, and is sensitive to the FF ratio. The theoretical calculation [7] that uses free proton FFs reproduced very well the observed deviations from the free proton ratio, suggesting that they stem mainly from FSI. However, while the ratio of the polarization transfer components is sensitive (almost linearly) to the electromagnetic FFs ratio G_E/G_M, some nuclear effects may cancel out in the ratio. The measured individual polarization transfer components provide a more stringent test of the calculation.

Moreover, it was shown that the deviations of P_x/P_z measured on a bound proton in ^{2}H from that on a free proton, were in very good agreement with similar measurements on heavier nuclei, when using the proton virtuality as a universal parameter for these comparisons [8]. Such comparisons are improved by relating the data of each nucleus to a realistic model of the deuteron data, a process that requires the knowledge of the individual polarization transfer components [9]. We introduce such a model below.

In this work we report a new analysis of the ^{2}H$(\vec{e}, e'\vec{p})$ reaction measured at the Mainz Microtron (MAMI) over a wide range of missing momentum of the struck proton. Results of the polarization transfer ratio P_x/P_z deduced from these measurements were reported in [6]. In the new analysis, the beam polarization that was measured periodically during the experiment was determined in a continuous manner. The achieved accuracy was sufficient for extracting the individual polarization transfer components P_x, P_y and P_z, with a precision that can challenge theory.

The kinematics for the quasi-free elastic scattering off a bound nucleon is shown in Fig. 1. The reaction plane is 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}. The incident and scattered electron momenta that define the scattering plane are indicated by $\vec{k}$ and $\vec{k}'$. The initial and outgoing proton momenta are indicated by $\vec{p}_i$ and $\vec{p}_p$, respectively. The missing momentum is $\vec{p}_{\text{miss}} = \vec{q} - \vec{p}_p$. The missing momentum ($p_{\text{miss}}$) is taken to be positive (negative) if a component of $\vec{p}_{\text{miss}}$ is parallel (anti-parallel) to the momentum-transfer vector. In the impulse approximation with no FSI one has $\vec{p}_{\text{miss}} = -\vec{p}_i$. Following the convention of [6,8] the polarization components reported here are perpendicular to the scattering plane ($\hat{y}$) and in the scattering plane along ($\hat{z}$) and perpendicular ($\hat{x}$) to $\vec{q}$.

The experiment was performed on the MAMI A1 beam line using a liquid deuterium target and two of the A1 high-resolution spectrometers [10]. Polarized continuous wave (CW) electron beams of 600 MeV and 630 MeV were used with currents of 10 µA. The target was an oblong cell (50 mm long, 11.5 mm in diameter) filled with liquid deuterium. The spectrometers have momentum acceptances of 20–25% with solid angles of 28 msr and were used to detect the scattered electrons and the knocked out protons in coincidence. The proton spectrometer was equipped with a so called "focal-plane polarimeter" (FPP) placed behind its focal-plane, with a 7 cm thick carbon analyzer [10,11]. The spin dependent scattering of the polarized proton by the carbon analyzer enabled the determination of the transverse polarization components at the focal plane [11]. 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 [11].

The measurements covered two Q^2 ranges and two beam energies, in order to span a wide range of p_{miss}. For further details see [12].

The beam polarization at MAMI is obtained by using strained GaAs photocathodes. The beam polarization increases throughout the usage of the single cathode, due to the decrease of its quantum efficiency [13,14]. The beam polarization was measured daily using a Møller polarimeter located upstream of the target cell [15,16]. The measurements during the three weeks of the experimental run are shown in Fig. 2, where the slow increase in time is clearly seen. The statistical uncertainty on each measurement is about 1.5%, but there is an overall systematic uncertainty of a few percent, due to the calibration of the detectors in the Møller polarimeter. These measurements were fitted by a linear function ($\chi^2/\text{ndf} = 60.2/61$).

In addition to the Møller measurements, the beam polarization was measured for each beam energy by Mott scattering [17]. The Mott and Møller measurements are consistent (see Fig. 2).

To determine the overall normalization of the beam polarization and the analyzing power, we use measurements of the polarization transfer to a free proton by ^{1}H$(\vec{e}, e'\vec{p})$, which were performed in the beginning of the run (indicated by the red time interval in Fig. 2) at $Q^2 = 0.4$ GeV^2/c^2. Assuming the FF ratio G_E/G_M for a free proton from the parameterization of [18] (estimated uncertainty of 0.5%), we deduced the beam polarization from the polarization transfer for these measurements. The resultant overall normalization was 1.00 ± 0.01. The uncertainty is dominated by the statistical uncertainty of our hydrogen measurements. The band in Fig. 2 shows the overall uncertainty of the beam polarization.

In the analysis of the polarization components, cuts were applied to identify coincident electrons and protons that originate from the deuterium target, and to ensure good reconstruction of tracks in the spectrometers and the FPP. Only events that scatter by more than 10° in the FPP were selected (to remove Coulomb scattering events in the FPP carbon analyzer). For each event we used the beam polarization obtained from the time-dependence fit.

Time-independent corrections to the polarization transfer measurements (acceptance, detector efficiency, target density, etc.) are largely canceled out by the frequent flips of beam helicity. Contributions to the systematic uncertainty due to the carbon analyzing power and FPP efficiency are well below the statistical uncertainty. The total systematic uncertainties in P_x and P_z are estimated to be about 2% and are due to beam polarization uncertainty (canceled in the P_x/P_z ratio) and the reaction vertex reconstruction (which dominates both the momentum resolutions and the spin-precession evaluation). The systematic uncertainty on P_y is estimated to be comparable to the statistical one.

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