Spin-Momentum Correlations in Quasielastic Electron Scattering from Deuterium

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The spin-momentum correlation parameter $A_{\rm ed}^V$ was measured for the $^2\vec{\rm H}(\vec{e}, e'p)n$ reaction for missing momenta up to 350 MeV/c at $Q^2 = 0.21$ (GeV/c)^2 for quasielastic scattering of polarized electrons from vector-polarized deuterium. The data give detailed information about the deuteron spin structure and are in good agreement with the results of microscopic calculations based on realistic nucleon-nucleon potentials and including various spin-dependent reaction mechanism effects. The experiment reveals in a most direct manner the effects of the D state in the deuteron ground-state wave function and shows the importance of isobar configurations for this reaction.

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The deuteron serves as a benchmark for testing nuclear theory. Observables such as its binding energy, static magnetic dipole and charge quadrupole moment, asymptotic D/S ratio, and the elastic electromagnetic form factors place strong constraints on any realistic nuclear model. Its simple structure allows reliable calculations to be performed in both nonrelativistic and relativistic frameworks [1–6]. Such calculations are based upon state-of-the-art nucleon-nucleon (NN) potentials [7–10], and the resulting ground-state wave function is dominated by the S state, especially at low relative proton-neutron momentum $\mathbf{p}$ in the center of mass system. Because of the tensor part of the NN interaction a D-state component is generated (see, e.g., [5,11]). The models predict that the S- and D-state components strongly depend on $\mathbf{p}$ and are sensitive to the repulsive core of the NN interaction at short distances [5].

Traditionally, the spin structure of the deuteron has been studied through measurements of the tensor analyzing power T_{20} [12–18] in elastic electron-deuteron scattering. Complementary information can be obtained by electrodisintegration studies in the region of quasielastic scattering. In the $^2{\rm H}(e, e'p)n$ reaction, energy ν and three-momentum $\mathbf{q}$ are transferred to the nucleus and the nuclear response can be mapped as a function of missing momentum $\mathbf{p}_m$ and missing energy. Here, $\mathbf{p}_m \equiv \mathbf{q} - \mathbf{p}_f$ and $\mathbf{p}_f$ represents the momentum of the ejected proton. In the plane-wave impulse approximation (PWIA) the neutron is a spectator only during the scattering process, and $\mathbf{p}_m$ is equal to the initial proton momentum in the deuteron, while the missing energy equals the binding energy. In this way the $(e, e'p)$ reaction has been employed to probe the proton inside the deuteron for momenta up to 1.0 GeV/c [19–21].

To enhance the sensitivity to the spin structure of the deuteron, spin dependent observables in quasielastic scattering can be used [5,22,23]. The polarization of a proton P_z^p inside a deuteron with a vector polarization P_1^d, is given by [24]

$$P_z^p = \sqrt{\frac{2}{3}}\, P_1^d\Big(P_S - \frac{1}{2} P_D\Big), \tag{1}$$

where P_S and P_D, respectively, represent the S- and D-state probability densities of the ground-state wave function. Note that the polarization of a nucleon in the D state is opposite to that of a nucleon in the S state.

The cross section for the $^2\vec{\rm H}(\vec{e}, e'p)n$ reaction, in which longitudinally polarized electrons are scattered from a polarized deuterium target, can be written as [22]

$$\sigma = \sigma_0\{1 + P_1^d A_d^V + P_2^d A_d^T + h(A_e + P_1^d A_{\rm ed}^V + P_2^d A_{\rm ed}^T)\}, \tag{2}$$

where σ_0 represents the unpolarized cross section, h the polarization of the electrons, and P_1^d (P_2^d) the vector (tensor) polarization of the target. The beam analyzing power is denoted by A_e, with $A_d^{V/T}$ and $A_{\rm ed}^{V/T}$ the vector and tensor analyzing powers and spin-correlation parameters, respectively. These target analyzing powers and spin-correlation parameters depend on the orientation of the target spin, e.g., $A_{ed}^{V/T}(\theta_d, \phi_d)$. The angles θ_d and ϕ_d define the polarization direction of the deuteron in the frame where the z axis is along the direction of $\mathbf{q}$ and the y axis is defined by the cross product, $\mathbf{k} \times \mathbf{k}'$, of the incoming and outgoing electron momenta as shown in Fig. 1.

In PWIA the asymmetry A_{ed}^V in the cross section only depends on the polarization of the proton in the deuteron given in Eq. (1), the kinematics of the scattering process, and on the electromagnetic form factors of the proton [25]. These form factors are well known [26–30] (see also references therein) for the kinematics used in the present experiment. It is therefore possible to calculate A_{ed}^V with high precision. However, the naive PWIA results must be modified to include the contributions from the neutron (plane-wave Born approximation or PWBA) and to account for spin-dependent reaction mechanism effects such as final-state interactions (FSI), meson-exchange currents (MEC), and isobar configurations (IC), while relativistic corrections (RC) need to be applied [6]. In this Letter, we report on the first measurement of A_{ed}^V in the $^2\vec{\mathrm{H}}(\vec{e}, e'p)n$ reaction.

The experiment was performed with a polarized gas target internal to the Amsterdam Pulse-Stretcher (AmPS) electron storage ring [31]. Polarized electrons were produced by photoemission from a strained-layer semiconductor cathode (InGaAsP) [32], accelerated to 720 MeV, and injected in the AmPS storage ring. By injecting multiple electron bunches into the storage ring, beam currents of more than 100 mA with a lifetime in excess of 15 min were obtained. The polarization of the stored electrons was maintained by setting the spin tune to 0.5 with a strong solenoidal field, using the Siberian snake principle [33] and was monitored regularly by using laser backscattering [34]. In order to avoid a systematic uncertainty associated with possible beam polarization losses and to maintain a high average beam current, the stored electrons were dumped every 5 min, and the ring was refilled after reversal of the electron polarization at the source.

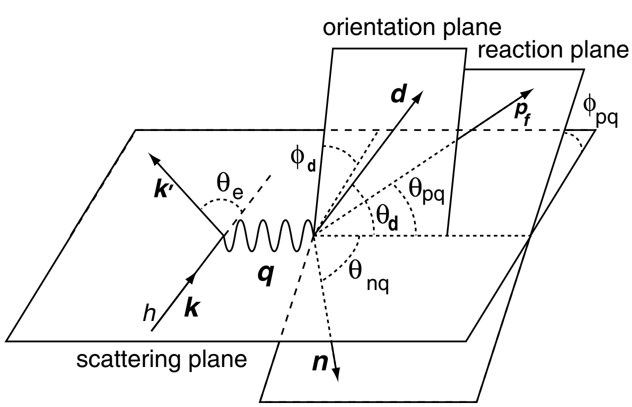

FIG. 1. Scattering kinematics for quasielastic polarized electron scattering from vector polarized deuterium. The target spin vector is represented by $\mathbf{d}$, while $\mathbf{n}$ represents the neutron.

An atomic beam source (ABS) produced a flux of 3×10^{16} deuterium atoms/s in two hyperfine states [35]. These polarized atoms, analyzed by a Breit-Rabi polarimeter [35], were fed into a cylindrical storage cell cooled to 75 K. The cell had a diameter of 15 mm and was 60 cm long, resulting in a typical target thickness of 1×10^{14} deuterons/cm^2. An electromagnet was used to provide a guide field of 40 mT over the storage cell. In order to measure $A_{ed}^V(90°, 0°)$, the deuteron polarization axis was oriented in the scattering plane and perpendicular to the $\mathbf{q}$ direction. The vector polarization of the target, $P_1^d = \sqrt{3/2}\,(n_+ - n_-)$, with $n_\pm$ the fraction of deuterons with spin projection ± 1, was varied every 10 sec, while keeping the tensor polarization fixed.

Scattered electrons were detected in the large-acceptance magnetic spectrometer BigBite [36] with a momentum acceptance from 250 to 720 MeV/c and a solid angle of 96 msr as shown in Fig. 2. BigBite was positioned at a central scattering angle of 40°, resulting in a central value of $Q^2 \equiv \mathbf{q}^2 - \nu^2 = 0.21$ (GeV/c)^2.

Knocked-out protons were detected in a time-of-flight (TOF) system made of a scintillator array, consisting of four 160 cm long, 20 cm high, and 20 cm thick vertically stacked plastic scintillator bars. Each bar was preceded by two (δE and ΔE) plastic scintillators (3 and 10 mm thick, respectively) of equal length and height, used for particle identification. Each of the scintillators was read out at both ends to obtain position information along the bars (resolution ~4 cm) and good coincidence timing resolution (~0.5 ns). The TOF detector was positioned at a

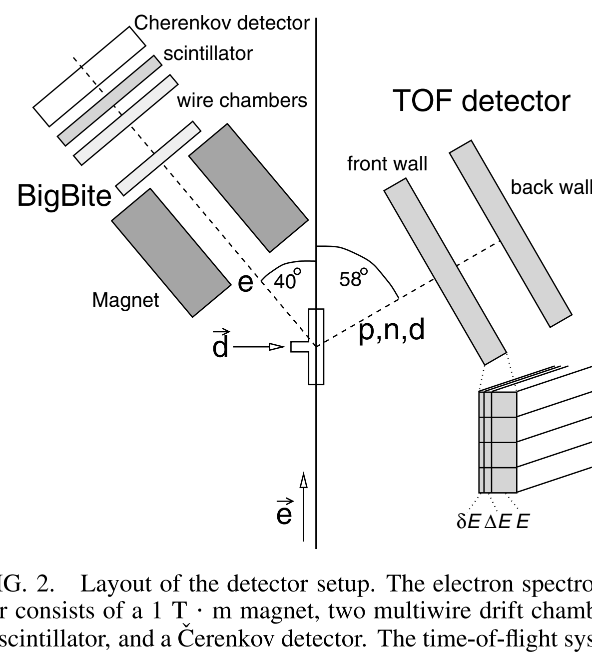

FIG. 2. Layout of the detector setup. The electron spectrometer consists of a 1 T · m magnet, two multiwire drift chambers, a scintillator, and a Čerenkov detector. The time-of-flight system consists of two identical walls of four E-scintillators preceded by two (δE and ΔE) veto scintillators. The second wall was used only for neutron detection, as described in Ref. [37].

central angle of 58° and covered a solid angle of about 250 msr.

Protons with kinetic energies in excess of 40 MeV were detected with an energy resolution of about 10%. The $e'p$ trigger was formed by a coincidence between the electron arm trigger and a hit in any one of the TOF bars. Protons were selected by a valid hit in two photomultipliers (PMTs) of at least one E-bar and a valid hit in both PMTs of one of the preceding ΔE bars. This requirement allowed us to use ΔE-E particle identification to discriminate between protons and either deuterons or pions. To select the two-body breakup, the electron energy was required to be larger than 450 MeV with a reconstructed missing energy between -50 and 50 MeV. Note that missing energy is defined as $E_m \equiv \nu - T_p - T_n$, where T_p and T_n represent the kinetic energies of the ejected proton and recoiling neutron, respectively. These requirements resulted in clean two-body breakup events, with only a small dilution due to cell-wall events.

The spin correlation parameter $A_{\rm ed}^V(90°, 0°)$ was extracted from the measured asymmetry via

$$A_{\rm exp} = \frac{N_{++} + N_{--} - N_{+-} - N_{-+}}{N_{++} + N_{--} + N_{+-} + N_{-+}} = hP_1^d A_{\rm ed}^V, \quad (3)$$

where $N_{\pm\pm}$ represent the number of events that pass the selection criteria, with h and P_1^d either positive or negative, normalized to the integrated luminosity in that configuration. The contribution of electrons scattering from the cell wall has been taken into account by subtracting the normalized rate of cell-wall events from the observed number of events. We have studied the cell-wall contribution by measuring with an empty storage cell. The background contribution amounted to 5% for low missing momenta, increasing to about 40% for $p_m = 400$ MeV/c. A possible dependence on the target density was investigated by injecting various fluxes of unpolarized hydrogen into the cell and measuring quasielastic nucleon knockout events. The target density dependence was found to be negligible at ABS operating conditions. Finite-acceptance effects were taken into account from the results of a Monte Carlo code that interpolated the model predictions in a dense grid over the full kinematical range and detector acceptance.

Figure 3 shows the experimental results in comparison to various predictions. The short-dashed and dot-dot-dashed curves are PWIA predictions for the Argonne v_{18} *NN* potential [10] with and without inclusion of the D state, respectively. The figure shows that inclusion of the D state is essential to obtain a fair description of the data for the higher missing momenta. The other curves are predictions of the model of Arenhövel *et al.* [6,22] for the Bonn *NN* potential [7] and with different descriptions for the spin-dependent reaction mechanism. We have investigated the dependence of the predictions on the *NN* potential for the Bonn [7], Nijmegen [8], Paris [9], and Argonne

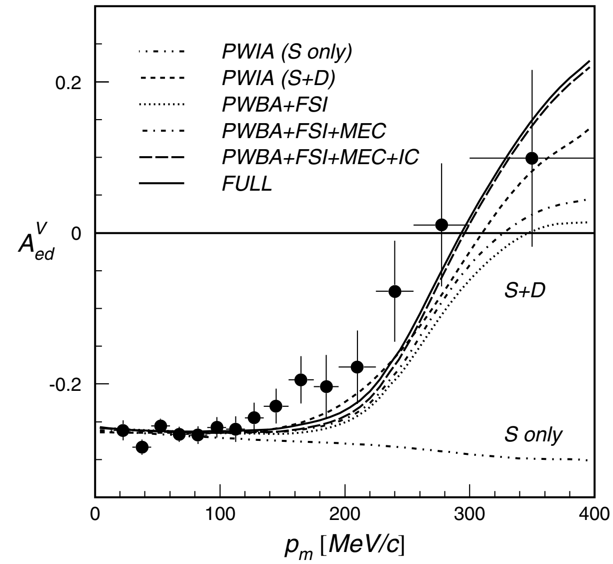

FIG. 3. Spin correlation parameter $A_{\rm ed}^V(90°, 0°)$ as a function of missing momentum for the $^2\vec{\rm H}(\vec{e}, e'p)n$ reaction at $Q^2 = 0.21$ (GeV/c)^2. The short-dashed and dot-dot-dashed curves are PWIA predictions for the Argonne v_{18} *NN* potential [10] with and without inclusion of the D wave, respectively. The other curves are predictions of the model of Arenhövel *et al.*, for PWBA + FSI (dotted), PWBA + FSI + MEC (dashed-dotted), PWBA + FSI + MEC + IC (long-dashed), and FULL calculations which include RC (solid), as indicated in Refs. [6,22]. The predictions are folded over the detector acceptance by using a Monte Carlo method.

[10] potentials. The effect of these potentials on $A_{\rm ed}^V$ is negligible for $p_m < 200$ MeV/c, and increases to 0.04 for $p_m = 400$ MeV/c, much smaller than the accuracy of the data or the uncertainty in the calculation of the reaction mechanism effects.

At $p_m < 100$ MeV/c, the theoretical results for $A_{\rm ed}^V$ neither depend on the choice of the *NN* potentials nor on the models for the reaction mechanism. This shows that in this specific kinematic region the deuteron can be used as an effective neutron target. Thus, these data were normalized to the calculations and yielded an absolute accuracy of 3% in the determination of hP_1^d for our measurement of the charge form factor of the neutron [37]. For increasing missing momenta, both the data and predictions for the asymmetry reverse sign. This is expected from Eq. (1) for an increasing contribution from the D-state component in the ground-state wave function of the deuteron. It can also be observed that inclusion of reaction mechanism effects, mainly isobar configurations, are required for a better description of the data. This is in agreement with studies of unpolarized quasielastic electron-deuteron scattering [21,38–40].

In the region of p_m around 200 MeV/c where the S and D states strongly interfere, the data suggest that all models underestimate $A_{\rm ed}^V$. This may be attributed to an underestimate of the D-state contribution or to a lack in our understanding of the effects of Δ excitation. This observation may be related to the deficiency in the prediction of the deuteron quadrupole moment by modern *NN* potentials [7–11]. A similar deficit was observed in our measurements of T_{20} [17] (see also Fig. 11 in Ref. [41]), as well as in the recent measurements of the cross section for the $^2\mathrm{H}(e,e'p)n$ reaction at JLab [42].

In summary, we have presented, for the first time, data on the spin correlation parameter $A^V_{\mathrm{ed}}(90°, 0°)$ in quasielastic electron-proton knockout from the deuteron. The data are sensitive to the effects of the spin-dependent momentum distribution of the nucleons inside the deuteron. The experiment reveals in a most direct manner the effects of the D state in the deuteron ground-state wave function and shows the importance of isobar configurations for the $^2\vec{\mathrm{H}}(\vec{e},e'p)n$ reaction. It is well known that momentum densities are model dependent quantities and not observable. This applies as well for the magnitude of the D-state and isobar configurations. Nonetheless, these quantities are sensitive ingredients in current models that predict observables such as A^V_{ed}.

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