Spin-Momentum Correlations in Quasi-Elastic Electron Scattering from Deuterium

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We report on a measurement of spin-momentum correlations in quasi-elastic scattering of longitudinally polarized electrons with an energy of 720 MeV from vector-polarized deuterium. The spin correlation parameter $A_{Vd}$ was measured for the $^2\text{H}(e,e'p)n$ reaction for missing momenta up to 350 MeV/c at a four-momentum transfer squared of 0.21 (GeV/c)$^2$. The data give detailed information about the spin structure of the deuteron, and are in good agreement with the predictions of microscopic calculations based on realistic nucleon-nucleon potentials and including various spin-dependent reaction mechanism effects. The experiment demonstrates 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 non-relativistic and relativistic frameworks.[4] 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 $p$ in the center of mass system. Due to the tensor part of the NN interaction a $D$-state component is generated (see e.g. [11,12]). The models predict that the $S$- and $D$-state components strongly depend on $p$ and are sensitive to the repulsive core of the NN interaction at short distances.

Traditionally, the spin structure of the deuteron has been studied through measurements of the tensor analyzing power $T_{20}$ [12,13] in elastic electron-deuteron scattering. However, more direct access to the nucleon momentum densities is obtained by electrodisintegration studies in the region of quasi-elastic scattering. In the $^2\text{H}(e,e'p)n$ reaction, energy $\nu$ and three-momentum $q$ are transferred to the nucleus and the nuclear response can be mapped as a function of missing momentum $p_m$ and missing energy. Here, $p_m \equiv q - p_f$ and $p_f$ represents the momentum of the ejected proton. In this way the $(e,e'p)$ reaction has been employed to probe the deuteron for momenta up to 1.0 GeV/c [13,14]. In the plane-wave impulse approximation (PWIA) the neutron is only a spectator during the scattering process, and $p_m$ is equal to the initial proton momentum in the deuteron, while the missing energy equals the binding energy.

To enhance the sensitivity to the spin structure of the deuteron, spin dependent observables in quasi-elastic scattering can be used [12,13,14]. The polarization of a proton $P^e_D$ inside a deuteron with a vector polarization $P^e_1$, is given by [14]

$$P^e_D = \sqrt{\frac{2}{3}} P^e_1 (P_S - \frac{1}{2} P_D),$$

(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 $^2\text{H}(e,e'p)n$ reaction, in which longitudinally polarized electrons are scattered from a polarized deuterium target, can be written as [12]

$$S = S_0 \{ 1 + P^d_1 A^V_d + P^d_2 A^T_d + h ( A_c + P^d_1 A^V_{cd} + P^d_2 A^T_{cd} ) \} ,$$

(2)
where $S_0$ 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 $A$, with $A^V_{ed}$ and $A^T_{ed}$ 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. $A^V_{ed} \left( \theta_d, \phi_d \right)$. The angles $\theta_d$ and $\phi_d$ define the polarization direction of the deuteron in the frame where the $z$-axis is along the direction of $q$ and the $y$-axis is defined by the cross product, $k \times k'$, of the incoming and outgoing electron momenta as shown in Fig. 1.

In PWIA the asymmetry $A^V_{ed}$ 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 $f_q$. These form factors are well known $^{26,27}$ and described in Ref. [34].

The experiment was performed with a polarized gas target internal to the Amsterdam Pulse-Stretcher (AmPS) electron storage ring $^{32}$. Polarized electrons were produced by photo-emission from a strained-layer semiconductor cathode (InGaAsP) $^{33}$, 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 life time in excess of 15 minutes 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 $^{31}$ and was monitored regularly by using laser back-scattering $^{31}$. 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 minutes, and the ring was refilled after reversal of the electron polarization at the source.

An atomic beam source (ABS) produced a flux of $3 \times 10^{16}$ deuterium atoms/s in two hyperfine states $^{32}$. These polarized atoms, analyzed by a Breit-Rabi polarimeter $^{33}$, 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 $1 \times 10^{14}$ deuterons/cm$^2$. An electromagnet was used to provide a guide field of 40 mT over the storage cell.

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

In order to measure $A^V_{ed}(90^\circ, 0^\circ)$, the deuteron polarization axis was oriented in the scattering plane and perpendicular to the $q$ direction. The vector polarization of the target, $P_1^d = \sqrt{2}(n_+ - n_-)$, with $n_\pm$ the fraction of deuterons with spin projection $\pm 1$, was varied every 10 seconds, while keeping the tensor polarization fixed.

FIG. 2. Layout of the detector setup. The electron spectrometer consists of a 1 T-magnet, two multi-wire 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 ($\delta E$ and $\Delta E$) veto scintillators. The second wall was used only for neutron detection, as described in Ref. $^{34}$.

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Scattered electrons were detected in the large-acceptance magnetic spectrometer BigBite $^{32}$ 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 $Q^2 = q^2 - \nu^2 = 0.21$ (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 (\(\Delta E\) and \(\Delta E\)) 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 \(\sim 4\) cm) and good coincidence timing resolution (\(\sim 0.5\) ns). The TOF detector was positioned at a central angle of 58\(^\circ\) 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 one of the preceding \(\Delta E\) bars. This requirement allowed us to use \(\Delta E-E\) 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 reconstruction missing energy between \(-50\) MeV and 50 MeV. Note that missing energy is defined as \(\Delta E\equiv \nu - T_p - T_n\), 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 \(A_{ed}^V(90^\circ, 0^\circ)\) was extracted from the measured asymmetry via

\[
A_{exp} = \frac{N_{++} + N_{--} - N_{+-} - N_{-+}}{N_{++} + N_{--} + N_{+-} + N_{-+}} = \hbar P_1^d A_{ed}^V, \tag{3}
\]

where \(N_{\pm\pm}\) represent the number of events that pass the selection criteria, with \(\hbar\) 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 quasi-elastic nucleon knock-out 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.

Fig. 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 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. for the Bonn NN potential 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, Nijmegen, Paris and Argonne potentials. The effect of these potentials on \(A_{ed}^V\) 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 \(A_{ed}^V\) 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 \(\hbar P_1^d\) for our measurement of the charge form factor of the deuteron. For increasing missing momenta, both the data and predictions for the asymmetry reverse sign, as expected from Eq. (i) 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 re-

![Fig. 3. Spin correlation parameter \(A_{ed}^V(90^\circ, 0^\circ)\) as function of missing momentum for the \(^2\)H(\(e',e'p\))n reaction at \(Q^2 = 0.21\) (GeV/c)\(^2\). The short-dashed and dot-dot-dashed curves are PWIA predictions 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 Ref. (22). The predictions are folded over the detector acceptance by using a Monte Carlo method.](image-url)
action mechanism effects, mainly isobar configurations, are required for a better description of the data. This is in agreement with studies of unpolarized quasi-elastic electron-deuteron scattering.

In the region of $p_\text{m}$ around 200 MeV/c where the $S$- and $D$-states strongly interfere, the data suggest that all models underestimate $A_{Vd}^d$. This may be attributed to an underestimate of the $D$-state contribution or to a lack in our understanding of the effects of $\Delta$-excitation. This observation may be related to the deficiency in the prediction of the deuteron quadrupole moment by modern NN potentials. A similar deficit was observed in our measurements of $T_{20}$ (see also Fig. 11 in Ref. 17).

In summary, we have presented, for the first time, data on the spin correlation parameter $A_{Vd}(90^\circ,0^\circ)$ in quasi-elastic electron-proton knock-out 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 for the spin-dependent momentum distribution of the nucleons inside the deuteron. This may be attributed to a lack in our understanding of the effects of $\Delta$-excitation. This may be attributed to the deficiency in the prediction of the deuteron quadrupole moment by modern NN potentials. A similar deficit was observed in our measurements of $T_{20}$ (see also Fig. 11 in Ref. 17).

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