Angular dependence of recoil proton polarization in high-energy $\gamma d \to pn$

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We measured the angular dependence of the three recoil proton polarization components in twobody photodisintegration of the deuteron at a photon energy of 2 GeV. These new data provide a benchmark for calculations based on quantum chromodynamics. Two of the five existing models have made predictions of polarization observables. Both explain the longitudinal polarization transfer satisfactorily. Transverse polarizations are not well described, but suggest isovector dominance.

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An important question to nuclear physics is whether one can understand exclusive nuclear reactions starting from quantum chromodynamics (QCD), or at least QCD-inspired quark models. Several studies of nuclei [1–4] at high momentum transfer, but in elastic or quasifree kinematics, have shown that the role of explicit quark degrees of freedom is subtle and elusive; even data that probe short ranges can be understood with hadronic theories with the underlying interactions determined from the measured $NN$ force and other inputs. Deuteron photodisintegration is unique among exclusive reactions, in that it has been measured at both large momentum transfer and large energies. Experiments [5–10] have shown that the cross section in the GeV region scales, approximately following the constituent counting rules [11, 12], as would be expected if the underlying dynamics involved quark degrees of freedom. The large energies involve a sum over large numbers of baryonic resonances, leading naturally to the idea of using quark degrees of freedom to explain the data, although perturbative QCD is not expected to apply [13].

Several quark model calculations [14–18] give competing approximate explanations of the photodisintegration cross sections. All but one are based on the idea that the high energy photon is absorbed by a pair of quarks being interchanged between the two nucleons; the quark-gluon string (QGS) model [15] uses Regge theory to evaluate 3-quark exchange. The models calibrated by the measured $NN$ force [15, 16, 18] tend to better reproduce the cross sections than the models which evaluate the quark-exchange diagram approximately [14, 17]. The reason [17] is that the data scale better with energy than one would expect for the measured energy range.

Polarization observables provide potentially stricter tests of the underlying dynamics [19, 20]. For example, the $\Sigma$ (linearly polarized photon) asymmetry, measured up to 1.6 GeV, is important for constraining the isoscalar vs. isovector nature of the photon coupling at high en-
energy [19]. For the recoil proton polarizations, measured at $\theta_{zm} = 90^\circ$ up to 2.4 GeV [22], the induced polarization $p_\gamma$ vanishes, but the polarization transfers $C_P$ and $C_P'$ do not, although they approach a slow approach to zero. Thus, while hadron helicity conservation (HHC) [23] does not hold, a slow approach to HHC cannot be ruled out, but it is not expected [24]. Very small induced polarizations, consistent with the data, were predicted by the hard rescattering (HR) model [20], based on modeled $pn$ helicity amplitudes. Here, we present new data at large energy and four-momentum transfer, to further test the theoretical models. These data are the only polarization angular distribution in deuteron photodisintegration measured significantly above 1 GeV.

The experiment (E00-007) ran in Hall A of the Thomas Jefferson National Accelerator Facility (JLab) [25]. A strained GaAs crystal produced the longitudinally polarized electron beam. The beam helicity state was flipped pseudo-randomly at 30 Hz. Beam charge asymmetries between the two helicity states were negligible. The Hall A Möller polarimeter determined the average beam polarization, $P_e$, to be $76\% \pm 0.3\%$ (statistics) $\pm 3.0\%$ (systematics).

Circularly polarized bremsstrahlung photons were generated when the 2.057-GeV electron beam impinged on a copper radiator with a thickness of 6% radiation length, located 20 cm upstream of the center of a 15-cm liquid deuterium target. The ratio of the photon polarization $P_\gamma$ to $P_e$ is calculable [26]; here $P_\gamma/P_e \approx 99.5\%$.

Recoil protons from the target were detected in the Hall A left high resolution spectrometer (HRLS) at the five kinematic settings listed in Table I. The scattering angles, momentum, and interaction position at the target were calculated from trajectories measured with Vertical Drift Chambers (VDCs) located in the focal plane. Two planes of plastic scintillators provided triggering and flight time information for particle identification. The incident photon energy was reconstructed from the scattered proton momentum and angle using two-body photodisintegration kinematics. Only events between the bremsstrahlung endpoint and the pion production threshold were used in the analysis.

The final element in the detector stack was the focal plane polarimeter (FPP) [27]. To improve its efficiency, we configured the polarimeter with a dual analyzer system, as in [28]. The VDC chambers, a 44-cm thick polyethylene (CH$_2$) analyzer, and front straw chambers constituted the first polarimeter, while the front straw chambers, a 49.5-cm carbon analyzer, and rear straw chambers constituted a second, independent polarimeter.

The HRLS spectrometer transverse angle and transverse position resolutions (FWHM) are 2.6 mrad and 4 mm, respectively [25]. Events originating from the target windows were eliminated by cuts on the interaction position. In addition to cuts based on particle’s position and direction at the target, a set of 2-dimensional pro-

| $(E_\gamma)$ $(\theta_{zm\gamma})$ | $p_\gamma$ | $(\theta_{lab\gamma})$ | spin | FPP parameter | elastic $\vec{ep}$ |
|---------------------|-------|----------------|----|-------------|------------------|
| GeV | GeV/c | | | precession analyzer calibration |
| 2.01 | 36.9° | 2.41 | 19.8° | 226.5° | dual | yes |
| 2.00 | 52.8° | 2.24 | 29.1° | 209.6° | dual | yes |
| 1.99 | 69.8° | 2.01 | 30.7° | 191.9° | dual | yes |
| 1.97 | 89.8° | 1.68 | 53.9° | 167.1° | dual | yes |
| 1.94 | 109.5° | 1.35 | 70.6° | 144.2° | carbon | no |

Table II: The figure of merit (FOM), $\epsilon A^2$, efficiency times analyzing power squared, in %, and the proton form factor ratios obtained from the $ep$ calibration runs. The FOM relative statistical uncertainties are $\approx 15\%$. Statistical uncertainties dominate the form factor ratio uncertainty. $T_{\text{analy}}$, in GeV, is the proton kinetic energy at the mid-point of each analyzer.

Calibration runs used $\vec{ep} \rightarrow e\vec{p}$ elastic scattering at 4 GeV for four of the five spectrometer momentum settings of this experiment. Polarization transfer in elastic $\vec{ep}$ scattering determines both the ratio of the proton...
electromagnetic form factors [35–38] and the FPP calibration, after accounting for beam polarization and spin transport through the spectrometer; see Table II. Our measurements agree well with previous data for analyzing powers of carbon and CH$_2$ analyzers [27, 28, 39, 40] and for the form factor ratio [27]. For the $\gamma d$ data at $\theta_{cm} = 109.5^\circ$, only the carbon analyzer was used due to the low outgoing proton momentum; the analyzing power was taken from an earlier $\vec{e}p$ calibration run with the same FPP set up [34]. For the four kinematics with dual analyzers, recoil polarizations were consistent between the two analyzers within uncertainties, and the weighted averages are given as the final results in Table III.

**TABLE III:** Center-of-mass frame proton recoil polarization components, with statistical and systematical uncertainties.

| $\theta_{cm}$  | $p_y$       | $C_x$       | $C_z$       |
|----------------|-------------|-------------|-------------|
| $36.9^\circ$   | -0.301 ± 0.053 | -0.170 ± 0.041 | 0.654 ± 0.056 |
|                | ± 0.029      | ± 0.020     | ± 0.051     |
| $52.9^\circ$   | -0.209 ± 0.041 | -0.205 ± 0.040 | 0.573 ± 0.071 |
|                | ± 0.052      | ± 0.031     | ± 0.092     |
| $69.8^\circ$   | 0.008 ± 0.033 | -0.228 ± 0.045 | 0.835 ± 0.108 |
|                | ± 0.039      | ± 0.033     | ± 0.116     |
| $89.8^\circ$   | -0.090 ± 0.049 | 0.065 ± 0.074 | 0.453 ± 0.162 |
|                | ± 0.045      | ± 0.034     | ± 0.065     |
| $109.5^\circ$  | 0.226 ± 0.073 | 0.316 ± 0.082 | 0.001 ± 0.119 |
|                | ± 0.053      | ± 0.035     | ± 0.037     |

There are several systematic uncertainties. The statistical uncertainties of the measured analyzing powers dominate over the beam polarization uncertainty. Spectrometer offsets also contribute. Potential geometrical biases are eliminated by requiring that all possible secondary scattering proton azimuthal angles ($\phi_{FPP}$) fall into the boundaries of the polarimeter. The induced polarization $p_y$ in $ep$ elastic scattering vanishes – neglecting small effects from two-photon exchange – allowing a direct measurement of the false asymmetries in the polarimeter. The $ep$ induced polarization measurements were all consistent with vanishing, so the statistical accuracies of $p_y$ in the $ep$ calibration ($\leq 0.04$), were assigned as the false asymmetry systematic uncertainties of the induced polarization in deuteron photodisintegration. For the polarization transfer, the false asymmetries largely cancel in forming the helicity differences.

Figure 1 compares the proton recoil polarization of this work (E00-007), at $E_\gamma \approx 2$ GeV, with earlier results (Wijesooriya) [22] at $E_\gamma = 1.86$ GeV, and calculations. A slow energy dependence of the recoil polarizations above $E_\gamma \approx 1$ GeV was found in [22], and our new measurements at $\theta_{cm} = 90^\circ$ are compatible with the earlier results. All three polarization components are consistent with a smooth variation with angle, and with crossing

$$\sum_{i=1}^{6} \pm |F_{i,\pm}|^2,$$

with $f(\theta)$ the cross section. It is insensitive to phases of amplitudes. Except for the negative signs, $C_z'$ would equal the cross section, and could be predicted as reliably. In contrast, $C_x'$ and $p_y$ are the real and imaginary parts of the same sum of interfering amplitudes [13, 41], and are highly sensitive to phases, and difficult to predict.

Two calculations of the spin observables are available. Figure 1 shows that the QGS model [19] predicts a longitudinal polarization transfer in good qualitative agreement with the measured data, but makes no prediction for the transverse polarizations, due to their sensitivity to phases. Given the good agreement with deuteron photodisintegration cross sections in the few GeV region [10], the QGS model must be regarded as the most successful existing model of photodisintegration at a few GeV.

Figure 1 also shows predictions for all three observables from the HR model [20]. It should be noted that these calculations are at the lower edge of the nominal validity range of the model. Also, since the $pn$ spin amplitudes

![Figure 1](image_url)
are not well constrained by data, the $pn$ amplitudes are based on $pp$ data. Thus, there are large uncertainties in the predictions. One calculation (dotted line) assumes that there is only small helicity nonconservation, leading to small values of $C_{2'}$ and $p_y$, and $C_{2'}$ being nearly unity [43]. The second (dash-dot line) calculation assumes large helicity non-conservation. The comparison with all observables supports large helicity nonconservation, but clearly the predictions for the transverse polarization are not in sufficiently good agreement. However, ref. [20] points out that the transverse polarizations are not in sufficiently good agreement. However, the HR model does not agree quite as well as the QGS model in the $\Sigma$ asymmetry, mentioned above. While the HR model over the isoscalar channel, more so than in the calculation above about 3 GeV [13], and its $p_y$ predictions are consistent with the large-angle data.

To summarize, we provide new benchmark data for polarizations in deuteron photodisintegration. The two models which predict the longitudinal polarization transfer, the QGS and HR models, are in qualitative agreement with these data; while neither model adequately explains the transverse polarizations, the HR model indicates the qualitative behavior might arise from isovector dominance. High-energy photodisintegration of $pp$ pairs [42] is the next major test of the underlying dynamics and of the theoretical models, as these two models give very different predictions for $pp$ photodisintegration.

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presented in [13], which assumes $F_{1+} \approx F_{3-}$. 