Polarization in Photodisintegration of the Deuteron

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Abstract. Recoil proton polarization was measured in deuteron photodisintegration at $\theta_{\text{cm}} = 90^\circ$ for photon energies up to 2.4 GeV. The induced polarization p_y is consistent with vanishing above 1 GeV, in surprising disagreement with meson-baryon calculations. From pQCD it is generally expected that hadron helicity is conserved, but, the polarization transfer observables do not vanish. As the data are inconsistent with existing meson baryon model predictions, and with expectations from pQCD, we suggest that nonperturbative quark models will be needed to understand the underlying reaction dynamics.

INTRODUCTION

Whether a meson baryon or a quark gluon picture is more appropriate to describe high momentum transfer exclusive reactions is a fundamental issue in nuclear physics. It is often suggested that, at high momentum transfers / short distances, conventional meson baryon models will break down, and quark models will be needed. While self-consistent perturbative quantum chromodynamics (pQCD) calculations are believed to not generally describe exclusive reactions at currently accessible kinematics, various nonperturbative quark model approaches have been suggested.

The issue has been studied in several electromagnetic exclusive reactions at large momentum transfer, including deuteron photodisintegration [1], elastic electron deuteron scattering [2,3], and threshold deuteron electrodisintegration [4]. To date, the evidence is that meson baryon models work well, although sometimes the underlying reaction dynamics are ambiguous, as meson baryon and quark models give

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similar results. For example, in elastic ed scattering, polarization measurements [3] show that only meson baryon models can describe the data well up to $Q^2 = 1.7 \text{ GeV}^2$, while cross section measurements at higher momentum transfer [2] are consistent with both meson baryon calculations and quark models.

Similarly, in deuteron photodisintegration, the highest energy cross sections show an s^{-11} scaling behavior at $\theta_{\text{cm}} = 90^\circ$ that is consistent with a meson baryon calculation [5], a nonperturbative QCD model [6], and pQCD [7]. The onset of the scaling is at $-t \approx 1 \text{ GeV}^2$, which corresponds to a spatial resolution of $\approx 0.2 \text{ fm}$, and to a momentum transfer Q^2 of nearly 4 GeV^2 in ed elastic scattering [8].

Thus, we have measured recoil proton polarizations, with circularly polarized beam, to provide data that may be better able to discriminate among the various models that appear to explain the cross section measurements. We extend the range of induced polarization measurements from a maximum energy of near 1 GeV to about 2.4 GeV . We also present the first results for the double-polarization observables with circularly polarized beam and recoil proton polarization. Predictions for these observables are available from pQCD, and several meson baryon calculations of the induced polarization exist [9–13] – though only [12] extends the polarization predictions to energies above 1 GeV . Before the experiment ran, the general expectation was that pQCD predicts that the induced polarization vanishes, while the meson baryon calculations predict that resonance contributions lead to an induced polarization that is generally large and strongly energy dependent. Calculations are also underway in nonperturbative quark models [14,15].

In pQCD, vector interactions conserve quark helicity; to the extent that orbital angular momentum effects can be neglected, quark helicity conservation then leads to hadron helicity conservation (HHC) [16]. (In contrast, there are recent arguments for hadronic reactions that quark exchange diagrams will lead to violation of HHC [17].) HHC requires that the sum of the components of the hadronic spins along their respective momentum directions is the same for both initial and final states, and gives predictions for some spin observables. In particular, the recoil polarization induced component p_y and polarization transfer component C_x vanish. This can be seen from the expressions for these polarization components. There are 12 independent complex amplitudes. The induced polarization p_y and the polarization transfer C_x are proportional to the imaginary and real parts, respectively, of the same combination of amplitudes [18]. For example, p_y is given by

$$f(\theta)p_y = 2\Im \sum_{i=1}^3 [F_{i,+}^* F_{i+3,-} + F_{i,-} F_{i+3,+}^*], \quad (1)$$

with $f(\theta) = \sum_{i=1}^6 \sum_{\pm} |F_{i,\pm}|^2$. The hadron helicity conserving amplitudes are $F_{1,+} = \langle \lambda_p \lambda_n | T | \lambda_\gamma \lambda_d \rangle = \langle \frac{1}{2} \frac{1}{2} | T | 11 \rangle$, $F_{3,-} = \langle -\frac{1}{2} - \frac{1}{2} | T | 1 - 1 \rangle$, and $F_{5,\pm} = \langle \pm \frac{1}{2} \mp \frac{1}{2} | T | 10 \rangle$. Thus, each helicity-conserving amplitude multiplies a helicity non-conserving amplitude, and both observables vanish in case of HHC. The polarization transfer C_z is given by

$$f(\theta)C_z = \sum_{i=1}^6 \sum_{\pm} \pm |F_{i\pm}|^2. \quad (2)$$

With HHC, $f(\theta)C_z \rightarrow F_{1,+}^2 - F_{3,-}^2 + F_{5,+}^2 - F_{5,-}^2$, which is generally nonzero. However, at $\theta_{cm} = 90^\circ$, relations are expected between the helicity conserving amplitudes [19]. Both $F_{1,+}$ and $F_{3,-}$ should be small, since they couple an initial state of $S = 0$ or 2 to a final state of $S = 1$, thus requiring orbital angular momentum effects. $F_{5,+}$ and $F_{5,-}$ should be nearly equal, since the difference between the two amplitudes is only that the proton and neutron helicities are reversed. Thus, C_z should also approximately vanish with HHC.

We consider now the most recently published cross section data, from Hall C at the Thomas Jefferson National Accelerator Facility (JLab) [1], to illustrate the variety of physical models in which explanations of photodisintegration have been attempted. Fig. 1 presents existing high energy cross section data, and partially illustrates the ambiguity in interpretation mentioned above.

- The cross sections at 90° and 69° follow the pQCD scaling law, although pQCD is generally not expected to describe exclusive reactions at energies of a few GeV.
- At 90° and for energies up to 1.6 GeV, the meson baryon model calculations of the Bonn group [12] (not shown) also is in very good agreement with the data.
- The asymptotic meson exchange model [5] (not shown) also generally agrees with the cross sections up to ≈ 3 GeV. The model will eventually break down, because it does not quite scale as s^{-11} . This model includes a conventional description of the deuteron plus an additional hard component, normalized to fit the data at 1 GeV. The hard component presumably results from the underlying quark degrees of freedom, and thus is perhaps better considered to be a hybrid model.

FIGURE 1. $s^{11}d\sigma/dt$ vs E_γ for different center of mass angles. Data and curves are described in the text.

- The quark gluon string (QGS) [20] model takes the reaction to be dominated by three quark exchange, which can be calculated with Regge trajectory approaches. This nonperturbative QCD model works well at small $-t$.
- The QCD rescattering model [6] is a large $-t$, large E_γ nonperturbative QCD model. It calculates absolute cross sections for photodisintegration from the deuteron wave function, the hard photo-quark coupling, and the nucleon-nucleon scattering amplitude, taken from nucleon nucleon data. Thus, this approach includes, through the nucleon nucleon data, soft nonperturbative physics. The resulting calculation (hatched region) describes the data well, even beyond the limits of the models validity.
- Miller [22] and Radyushkin [23] have independently shown how, in a meson baryon and in a nonperturbative quark exchange model, respectively, the cross section should more or less follow phase space factors multiplied by nucleon form factors. This behavior is not too different from pQCD, at least over a limited kinematic range. This helps explain why the data and calculations in different frameworks are similar.

EXPERIMENT

Experiment E89-019 [21] was done at JLab Hall A. Longitudinally polarized electrons were incident on a copper radiator, producing an untagged Bremsstrahlung beam of circularly polarized photons. The photons and electrons then struck a liquid deuterium target. Eight beam energies from 0.5 to 2.5 GeV were used. Protons from the target were detected at a center of mass angles near 90° in one of the Hall A high resolution spectrometers, equipped with a focal plane polarimeter (FPP). The photon energy was reconstructed from the measured proton momentum and scattering angle. Background contributions from the target windows and from electrodisintegration were subtracted. Events with final-state pions were excluded by requiring the reconstructed photon energy to be near the electron beam energy.

Polarized protons scatter in the FPP carbon analyzer with an azimuthal asymmetry. The distributions were analyzed by means of a maximum likelihood method to obtain the induced and transferred polarization components. Spin precession in the spectrometer magnetic fields and the helicity of the electron beam were taken into account.

The polarimeter calibration was checked with ep elastic scattering data at each of the eight momentum settings. In ep elastic scattering, the ratio of the proton electromagnetic form factors G_E and G_M determines the polarization transfer components, usually called P_l and P_t . The ratio of these two components also directly determines the ratio of the form factors G_E/G_M , and the magnitudes determine the product of beam helicity and polarimeter analyzing power, hA_C . Here, A_C indicates a carbon analyzer, as has been used in most previous intermediate energy polarimeters. With Møller polarimeter measurements of the beam helicity, A_C is

FIGURE 2. Induced polarization p_y in the $\bar{\gamma}d \rightarrow \bar{p}n$ reaction at $\theta_{cm} = 90^\circ$.

determined, and agrees well with previous work [24]. Note that, while A_C does not affect the extracted form factor ratio G_E/G_M , it does affect the size of the uncertainty of the ratio.

Neglecting two photon exchange, the ep scattering has no induced polarization; thus, it also directly measures the small instrumental asymmetries, providing small corrections to the induced polarization p_y . Uncertainty in the instrumental asymmetry model dominates the systematic uncertainties for the induced polarization, ± 0.04 . For the polarization transfer data, the false asymmetries largely cancel with the helicity difference, leaving a smaller systematic uncertainty of about ± 0.02 . The systematic uncertainties tend to be small, smaller than the statistical uncertainties, because the polarizations measured are generally small, and uncertainties related to the carbon analyzing power and beam polarization are multiplicative factors.

RESULTS

The preliminary result for the normal component p_y of the induced polarization is shown as triangles in Fig. 2. Our data agree with earlier lower energy measurements from Stanford [25], Tokyo [26], and Kharkov [18,27], but disagree with the higher energy Kharkov results [28]. The higher energy Kharkov data were taken under much more difficult conditions than our measurement, which featured much more extensive calibrations, and lower backgrounds. We find that the induced polarization is small, consistent with vanishing above $E_\gamma \approx 1$ GeV. The six highest energy data points average to -0.02 ± 0.02 .

The solid curve shows the result of the meson-baryon calculation of the Bonn group [12]. There is fair qualitative agreement between the calculation and the data in the Δ -resonance region, but we find no evidence in our data for the predicted

structure near 1 GeV. Instead, our p_y data appear to support HHC (dashed curve), and thus pQCD. In the Bonn calculation the structure results largely from the D_{13} and D_{33} resonances interfering with the Born amplitude. Since there are only a few resonances with large photo-nucleon couplings in this energy region, the disagreement is an unexpected result, and suggests that the meson-baryon picture, at least as calculated, is not applicable.

The question is to what extent the Bonn calculation can be considered reliable and representative of meson baryon theory in general, and thus whether one can conclude anything about the general applicability of meson baryon theory. The answer is probably that no general conclusions can be made at this time. In the Bonn calculation, and others [9–11,13], final state interactions appear to have small effects on p_y . It should be noted that these models generally start from older potentials, derived largely from nucleon nucleon scattering up to 350 MeV. To match s , one considers nucleon nucleon scattering at a beam energy twice the photon energy; nucleon nucleon scattering at 2 - 5 GeV is highly inelastic, and thus probably the final state interactions in these calculations are not under good control.

If the final state interactions are indeed small, the Born amplitude is largely real, and the resonance – Born interference generates the induced polarization. The induced polarization results from the imaginary part of an interference of amplitudes, and one expects that isolated resonances lead to an energy dependent polarization that is maximal at the peak of the resonance. Especially since polarizations are more sensitive to the resonances than are the cross sections, overlapping resonances including those with small photo-couplings will change the detailed predictions from this simple picture.

The Bonn calculation includes π , ρ , η , and ω exchange, plus 17 well-established nucleon and Δ resonances with mass less than 2 GeV and $J \leq 5/2$, for which resonance parameters were taken from the Particle Data Group. Earlier polarization calculations [9–11], which included only the Δ resonance, have similar predictions to [12] at low energies. The inclusion of the Roper, S_{11} , and D_{13} was studied in [13], also with similar predictions to [12]. Thus, there is qualitative agreement between several calculations and the intuitive expectation.

Given approximations in the calculations, which are not discussed, uncertainties in resonance parameters, and possible problems in final state interactions, it is clear that one cannot conclude anything generally about whether meson baryon models are in principle capable of representing the induced polarization data shown above. We speculate, however, that hybrid models such as [5] are likely to succeed, since it appears that the cross section at large energies comes largely from the hard component of the deuteron, *if* final state interactions generate small polarizations in this framework.

Both the scaling of the cross section and the vanishing of p_y start near 1 GeV, and are consistent with pQCD predictions. Because of the failure of existing meson-baryon calculations, and the surprising agreement with HHC in a region in which pQCD is not expected to explain the data, further tests are required. More tests

FIGURE 3. Polarization transfer in the $\bar{\gamma}d \rightarrow \bar{p}n$ reaction at $\theta_{cm} = 90^\circ$, C_x (a) and C_z (b).

are possible with the polarization transfer observables C_x and C_z .

Our preliminary results are shown in Fig. 3; neither other data nor calculations exist. While C_z appears to approach zero near 2 GeV, the C_x data are non-zero and indicate that hadron helicity is *not* conserved in this energy range. The generally accepted expectation is that pQCD leads to HHC; thus we conclude that one should not try to explain the data as arising from pQCD. While this conclusion agrees with theoretical bias [29] that perturbative processes will lead to only a small fraction of the observed strength, we note here that there is a weakness to this argument. There are both nonperturbative and perturbative corrections to the pQCD polarization prediction of HHC that we have shown. For example, even neglecting possible orbital angular momentum contributions [17], one expects that there are perturbative quark helicity flip contributions [16]. Including these contributions will lead to a violation of HHC, but with a smooth approach to vanishing polarizations, which we cannot rule out.

We construct here a toy model to indicate how these observables could approach the HHC limit. Each helicity-flip should cause the amplitude to decrease faster by one power of t . This result is well known for the nucleon form factors, for which it is expected that $-tF_2/F_1$ approaches a constant at large $-t$. We assume the helicity conserving amplitudes have the form $F_i = A_i f(s, t)$, where A is a complex magnitude and $f(s, t)$ contains the kinematic variations. The leading corrections come from single helicity flip amplitudes, that we assume to have the form $F_j = A_j f(s, t)/t$. At sufficiently large $-t$ – possibly much larger than the range in this experiment – the cross section is dominated by non-helicity-flip amplitudes, and the expression given above for C_x can be seen to lead to a $1/t$ behavior. Presumably p_y vanishes in the data due to a lack of an imaginary part of the interference. With the additional assumptions of [19], C_z should approach zero like $1/t^2$. Figure 4 shows that these t dependences, *normalized* to the data, are in good, but not compelling agreement. Exploring this possibility further requires more precise data.

FIGURE 4. Polarization transfer in the $\gamma d \rightarrow \bar{p}n$ reaction at $\theta_{cm} = 90^\circ$, C_x (a) and C_z (b), compared to a toy model “prediction” of the approach to helicity conservation, normalized to the data.

We have shown above that existing MEC and pQCD do not predict the polarization data. We now consider several nonperturbative quark models, which have been applied to deuteron photodisintegration cross sections. The QCD rescattering model [6] provides absolute cross section calculations that agree with the data. The nonperturbative contributions are effectively included in the hard scattering pn amplitude, which is taken from the pn data. Preliminary induced polarization calculations [14] from this model indicate that p_y is small, for energies above about 2.5 GeV, as it is for E_γ from 1 to 2.4 GeV in the present data. There are also cross section calculations in the quark-gluon string model [30], and polarization calculations are underway [15]. The quark exchange model [31] suggests that the amplitudes are nearly real; this can explain p_y , but calculations are needed for C_x and C_z . The reduced nuclear amplitudes model [32] does not reproduce the cross sections well, and assumes helicity conservation, which would incorrectly predict that C_x vanishes.

CONCLUSIONS

The induced polarization above about 1 GeV is small, consistent with vanishing. The polarization transfers C_x and C_z are consistent with a steady decrease in magnitude starting slightly above 1 GeV, though the precision of the data is such that this result is not compelling.

These results have not been predicted in any theoretical approach. The induced polarization is clearly inconsistent with the only available high energy meson baryon polarization calculation. The results of this calculation are typical of what is seen in other meson baryon calculations, but one cannot rule out that an improved future calculation in this framework will agree with the data. No calculations of

polarization transfer exist for comparison.

The vanishing of the induced polarization is naturally explained by HHC within pQCD, but the polarization transfer observable C_x does not vanish. This clearly shows, with no assumptions, that HHC is not valid for deuteron photodisintegration in this energy region [33]. Thus, the data disagree with the usually expected behavior from pQCD. But the data do not rule out a possible perturbative approach to HHC, as demonstrated in a toy model.

If meson baryon theory and pQCD are both not applicable, then one is left by elimination with nonperturbative quark and hybrid models. These new benchmark data provide clear tests for the polarization calculations that will soon be available with these models.

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