The Deuteron Polarized Tensor Structure Function $b_1$

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Abstract. We describe Jefferson Lab E12-13-011, an inclusive deep inelastic scattering experiment to measure the leading twist deuteron tensor structure function $b_1$ in the region $0.16 < x < 0.49$ for $0.8 < Q^2 < 5.0$ GeV$^2$. The experiment has been conditionally approved, contingent on target performance, with A$^-$ physics rating to run with 30 days of 11 GeV incident beam on a tensor polarized solid target in Jefferson Lab’s Hall C.

1. Introduction

The deuteron is the simplest nuclear system and in many ways it is as important to understanding bound states in QCD as the hydrogen atom was to understanding bound systems in QED. Unlike its atomic analogue, our understanding of the deuteron remains unsatisfying both experimentally and theoretically. A deeper understanding of the deuteron's tensor structure will help to clarify how the gross properties of the nucleus arise from the underlying partons. This provides novel information about nuclear structure, quark angular momentum, and the polarization of the quark sea that is not accessible in spin-1/2 targets.

Four independent helicity amplitudes are sufficient to describe virtual Compton scattering from a spin-1/2 target, after requiring parity and time reversal invariance. This number doubles for a spin-1 target, where the spin can be in three states (+, 0, -). This gives rise to a tensor structure which was first discussed for the deuteron for the real photon case by Pais [1], and later in the virtual photon case, by Frankfurt and Strikman [2]. Hoodbhoy, Jaffe and Manohar [3] introduced the notation which we now follow, whereby the tensor structure is described by the four functions $b_1$, $b_2$, $b_3$ and $b_4$.

Of particular interest is $b_1$, which measures the extent to which the nuclear ground state deviates from being a simple collection of nucleons [4]: $b_1$ would vanish if the deuteron was simply a proton and neutron in a relative S state. At low $x$, shadowing effects are expected to dominate $b_1$, while at larger $x$-values where $b_1$ is anticipated to be small in conventional models, measurements provide a clean probe of exotic QCD effects.

There are several different approaches for predicting the $x$–dependent behavior of $b_1$ including one pion exchange [5], convolution models with relativistic and binding energy corrections [4], covariant relativistic calculations [6], double-scattering effects [7], and the virtual nucleon approximation [8]. All of these models predict a small or vanishing value at moderate $x$. However, the first measurement [9, 10] of $b_1$ at Hermes revealed a cross-over to a large negative value in the region $0.2 < x < 0.5$, albeit with relatively large experimental uncertainty. An atomic beam source was used to generate a deuterium gas target with high tensor polarization. The HERA storage ring provided 27.6 GeV positrons incident on the internal gas target.
As displayed in Fig. 1, (gray points) the tensor asymmetry $A_{zz}$ was found to be non-zero at about the two sigma level, with an apparent zero crossing around $x = 0.3$.

1.1. Hidden Color and 6-Quark Bags
Recently, Miller [11] showed that the Hermes data may indicate exotic effects from hidden color 6-quark configurations. See Fig. 1. Critically, it was demonstrated that no conventional nuclear mechanism can reproduce the large-$x$ Hermes data, but that the 6-quark probability needed to do so ($P_{6q} = 0.0015$) is small enough that it does not violate any known conventional nuclear physics. With this in mind, a precise measurement of $b_1$ could provide a unique and unambiguous signature of hidden color.

1.2. Virtual Nucleon and Light Cone Approximations
Following the approach of Ref. [2], M. Sargsian [8] has calculated the tensor asymmetry $A_{zz}$ for deep inelastic scattering. Within the PWIA approximation in which deuteron parton distributions are generated due to the partons in the proton and neutron, he predicts no significant tensor asymmetry except at very large $x$ (quasi-elastic scattering) in which case the D-wave becomes important. In the approximation in which only the proton-neutron component of the deuteron is taken into account and nuclear parton distributions are generated through the convolution of partonic distributions of the nucleon and deuteron density matrix (see e.g. Refs. [12, 13]), the deuteron structure function $b_1$ is related directly to the D-partial wave of the deuteron wave function [8, 12]. As a result, this approximation predicts negligible magnitude for $b_1$ for $x \leq 0.6$ due to the small Fermi momenta involved in the convolution integral. However, the predicted magnitude of $b_1$ is large at $x \geq 0.7$ where one expects substantial contribution from the D-waves due to the high momentum component of the deuteron wave function involved in the convolution picture of DIS scattering off the deuteron. In this case, $b_1$ is very sensitive to the relativistic description of the deuteron and its measurement can be used for checking the different approximations of the high momentum component of deuteron wave function.

In the calculation, either the Virtual Nucleon or Light-Cone approximations are used to calculate the tensor polarization for DIS scattering off the deuteron. In both approximations, only the proton-neutron component of the deuteron is taken into account. In the Virtual Nucleon approximation, the covariant scattering amplitude is reduced by estimating the spectator nucleon propagator at its on-energy shell in the lab frame of the deuteron. Within this approximation the baryonic sum rule is satisfied while the momentum sum rule is not. The latter is due to the fact that part of the light cone momentum of the bound virtual nucleon is lost to the unaccounted non-nucleonic degrees of freedom in the deuteron wave function. In the light cone approximation, the scattering amplitude is estimated as the $E + p_z$ pole of the spectator nucleon on the light cone. In this case the wave function is defined on the light-cone reference frame and it satisfies both baryon number and momentum sum rules. For a detailed comparison of these approximations, see Ref. [13].

1.3. The Close-Kumano Sum Rule
Kumano [14] pointed out that the twist-2 structure functions $b_1$ and $b_2$ can be used to probe orbital angular momentum. He then extracted the tensor polarized quark and anti-quark distributions from a fit to the Hermes data [9] and found that a non-negligible tensor polarization of the sea is necessary to reproduce the data.

Following the formalism from the parton model in [3], Close and Kumano [15] related the tensor structure function $b_1$ to the electric quadrupole form factor of the spin-1 target through a sum rule:

$$
\int_0^1 dx \ b_1(x) = - \frac{5}{12M^2} \lim_{t \to 0} t \ F_Q(t) + \frac{1}{9} \left( \delta Q + \delta \bar{Q} \right)_s
$$
\[ F_Q(t) = \frac{1}{9} \left( \delta Q + \delta \bar{Q} \right)_s = 0 \]  
(1)

where \( F_Q(t) \) is the electric quadrupole form factor of a spin-1 hadron at the momentum squared \( t \). The Close Kumano (CK) sum rule is satisfied in the case of an unpolarized sea. The authors note that in nucleon-only models, the integral of \( b_1 \) is not sensitive to the tensor-polarization of the sea, and consequently the sum rule is always true, even when the deuteron is in a \( D \)-state.

The authors of Ref. [4] calculated the first moment of \( b_1(x) \) in a version of the convolution model that incorporates relativistic and binding energy corrections. They found a value of \(-6.65 \times 10^{-4}\), and emphasize that deviations from this will serve as a good signature of exotic effects in the deuteron wave function. Similarly, Ref. [6] predicts \( 5 \times 10^{-4} \) and \( 3 \times 10^{-5} \) for the relativistic and nonrelativistic calculation of Eq. 1, respectively.

A truncated version of Eq. 1 was evaluated by the Hermes [9, 10] experiment and found to be

\[ \int_{0.0002}^{0.85} b_1(x) dx = 0.0105 \pm 0.0034 \pm 0.0035, \]  
(2)

which possibly indicates a breaking of the Close-Kumano sum rule, and consequently a tensor-polarized quark sea. However, since the comparison is only at the two sigma level, more precise data is needed for a true test.

1.4. Angular Momentum Sum Rule for Spin-1 Hadronic Systems

The \( b_1 \) structure function is connected with the spin-1 angular momentum sum rule as discussed in Ref. [16]. By examining the energy momentum tensor for the deuteron, the authors showed that it was possible to define an additional sum rule for \( b_1 \) (see Eq. 12 in Ref. [16]) where it was shown that the second moment of this quantity is non vanishing, being related to one of the gravitomagnetic deuteron form factors. A measurement of \( b_1 \) would provide a unique test of this idea.

It is also important to notice that \( b_1 \) singles out the role of the \( D \)-wave component in distinguishing coherent nuclear effects through tensor polarized correlations from the independent nucleon’ partonic spin structure. A similar role of the \( D \)-wave component was also found in the recently proposed spin sum rule where it plays a non-trivial role producing a most striking effect through the spin flip GPD E. An experimental measurement of \( b_1 \) would corroborate this scenario.

2. The Jefferson Lab E12-13-011 Experiment

E12-13-011 will perform an inclusive measurement of the deuteron tensor asymmetry \( A_{zz} \) in the region \( 0.16 < x < 0.49 \), for \( 0.8 < Q^2 < 5.0 \) GeV\(^2\) and invariant mass \( W \geq 1.85 \) GeV. A solid polarized ND3 target will be used, along with the Hall C spectrometers, and an unpolarized beam. The magnetic field of the target will be held constant along the beamline at all times, while the target state is alternated between a polarized and unpolarized state.

This measurement will provide access to the tensor quark polarization, probe hidden color, and provide data needed to test the Close-Kumano sum rule which has been predicted to be satisfied [15] in the absence of tensor polarization in the quark sea.

The experiment was given \( A^- \) physics rating and \( c_1 \) conditional approval by PAC 40. Efforts to address the \( c_1 \) condition to demonstrate 30% tensor polarization in a solid polarized target are underway at the Universities of Virginia and New Hampshire. A total of 30 days of beam time was approved for production data, with an additional 10.8 days of expected overhead.
2.1. Experimental Method

The measured DIS double differential cross section for a spin-1 target characterized by a vector polarization $P_z$ and tensor polarization $P_{zz}$ is expressed as

$$\frac{d^2\sigma_p}{dxdQ^2} = \frac{d^2\sigma}{dxdQ^2} \left( 1 - P_z P_B A_1 + \frac{1}{2} P_{zz} A_{zz} \right),$$

(3)

where $\sigma_p$ ($\sigma$) is the polarized (unpolarized) cross section, $P_B$ is the incident electron beam polarization, and $A_1$ ($A_{zz}$) is the vector (tensor) asymmetry of the virtual-photon deuteron cross section. This allows us to write the positive polarized tensor, $0 < P_{zz} \leq 1$, asymmetry using unpolarized electron beam as

$$A_{zz} = \frac{2}{P_{zz}} \left( \frac{\sigma_1}{\sigma} - 1 \right),$$

(4)

where $\sigma_1$ is the polarized cross section for

$$P_{zz} = \frac{n_+ - 2n_0 + n_-}{n_+ + n_- + n_0}, \text{ for } n_+ + n_- > 2n_0.$$

Here $n_m$ represents the portion of the ensemble in the $m$ state.

Eq. 4 reveals that the asymmetry $A_{zz}$ compares two different cross sections measured under different polarization conditions of the target, positively tensor polarized and unpolarized. To obtain the relative cross section measurement in the same configuration, the same target cup and material will be used at alternating polarization states (polarized vs. unpolarized), and the magnetic field providing the quantization axis will be oriented along the beamline at all times. This field will always be held at the same value, regardless of the target material polarization state. This ensures that the acceptance remains consistent within the stability ($10^{-4}$) of the super conducting magnet.

Since many of the factors involved in the cross sections cancel in the ratio, Eq. 4 can be expressed in terms of the charge normalized, efficiency corrected numbers of tensor polarized $N^c_1$ and unpolarized $N^c$ counts,

$$A_{zz} = \frac{2}{f P_{zz}} \left( \frac{N^c_1}{N^c} - 1 \right).$$

(6)
The dilution factor \( f \) corrects for the presence of unpolarized nuclei in the target, and the measured asymmetry is directly related to \( b_1 \) through

\[
b_1 = -\frac{2}{3} F_1^d A_{zz}. \tag{7}
\]

We can determine \( b_1 \) with sufficient precision to discriminate between conventional nuclear models and the more exotic behavior hinted at by the Hermes data, as shown in Figure 1. It is important to note that any significantly non-zero measured value of \( b_1 \) in this region is impossible to explain with conventional nuclear physics. It has also been emphasized that no known mechanism can predict a negative value for \( b_1 \) at any \( x \) [11]. On the other hand, a zero crossing is absolutely necessary for satisfaction of the Close-Kumano sum rule, so it is compelling to clarify the behaviour of \( b_1 \) at large \( x \).

2.2. Uncertainties
We expect scale dependent systematic uncertainties to contribute at the 9% relative level, dominated by the uncertainty arising from target polarimetry (8%) and dilution factor (4%).

Eq. 6 involves the ratio of counts, which leads to cancellation of several first order systematic effects. However, the fact that the two data sets will not be taken simultaneously leads to a sensitivity to time dependent variations which will need to be carefully monitored and suppressed. Full discussion of these effects can be found in Ref. [17].

3. Summary
E12-13-011 will determine \( b_1 \) with sufficient precision to discriminate between conventional nuclear models and the more exotic behavior which is hinted at by the Hermes data. The UVa solid polarized ND\(_3\) target will be used, along with the Hall C spectrometers, and an unpolarized beam. An additional 10.8 days will be needed for overhead. This measurement is sensitive to the tensor polarization of the quark sea, allows a test of the Close-Kumano sum rule, and provides a clean probe of hidden color. Until now, tensor structure has been largely unexplored, so the study of these quantities holds the potential of initiating a new field of spin physics at Jefferson Lab.

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