Tensor Asymmetry A_{zz} in the $x > 1$ Region

A Proposal to Jefferson Lab PAC 42

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Abstract

The tensor-polarized target asymmetry, A_{zz}, which is used to extract b_1 in the DIS region through the D(e, e')X channel, can be used to extract information on nucleon-nucleon interactions in the quasi-elastic region. The reaction is unique in that it can probe color transparency, which has never been explored at Jefferson Lab, and improve understanding of the deuteron wave function and particularly probe how short range correlations arise from proton-neutron interactions.

In the quasi-elastic region, A_{zz} was first calculated in 1988 by Frankfurt and Strikman, using the Hamada-Johnstone and Reid soft-core wave functions [1]. Recent calculations by M. Sargsian revisit A_{zz} in the $x > 1$ range using virtual-nucleon and light-cone methods, which differ by up to a factor of two [2].

An experimental determination of A_{zz} could be performed utilizing equipment identical for E13-12-011 at five different Q^2 values over the course of 24 days, with [NUMBER] additional days of commissioning. The measurements are less sensitive to the target polarization than E13-12-011, such that this experiment could be used to prove that the condition of 30% in-beam polarization is met for E13-12-011.

Contents

1 Quotes (To be removed)

"The most direct evidence for tensor correlations in nuclei comes from measurements of the deuteron structure functions and tensor polarization by elastic electron scattering [3]. In essence, these measurements have mapped out the Fourier transforms of the charge densitites of the deuteron in states with spin projections ± 1 and 0, showing that they are very different." -R. Schiavilla, et al. [4]

"The cross section for the double scattering process can be written as [5]

$$\frac{d\sigma}{d\Omega d\Omega_2} = \left.\frac{d\sigma}{d\Omega d\Omega_2}\right|_0 \left[1 + \frac{3}{2} h p_x A_y \sin\phi_2 + \frac{1}{\sqrt{2}} t_{20} A_{zz} - \frac{2}{\sqrt{3}} t_{21} A_{xz} \cos\phi_2 \right. \\ \left. + \frac{1}{\sqrt{3}} t_{22} \left(A_{xx} - A_{yy}\right) \cos 2\phi_2 \right] \tag{1}$$

where $h = \pm 1/2$ is the polarization of the incoming electron beam, ϕ_2 the angle between the two sattering planes (defined in the same way as the ϕ shown in figure 24) and A_y and the A_{ij} are the vector and tensor analysing powers of the second scattering. Although there is a p_z component to the vector polarization, the term is omitted from equation (25) as there is no longitudinal vector analysing power; without spin precession, this term cannot be determined." -R. Gilman and F. Gross [3]

"Accurate [form factor] measurements require that Q^2 be known accurately since A and B vary rapidly with Q^2. Energy or angle offsets of a few times 10^{-3} could lead to Q^2 being off by up to 0.5%. For both A and B, this leads to offsets that increase with Q^2, reaching about 2% at $Q^2 = 1$ GeV^2 and 4% at $Q^2 = 6$ GeV^2." -R. Gilman and F. Gross [3]

"The body of [A] data, aside from the lowest Q Orsay point, suggests the correctness of the Saclay measurements. Theoretical predictions span the range between the two data sets, and do not help to determine which is correct. Thus, a new high-precision experiment in this [higher] Q^2 range appears desirable." -R. Gilman and F. Gross [3]

"We are forced to conclude that these high Q^2 [form factor] measurements *cannot be explained by nonrelativistic physics and present very strong evidence for the presence of interaction currents, relativistic effects or possibly new physics*." -R. Gilman and F. Gross [3]

"It is now known that the tensor part of the one-pion exchange interaction is too strong to be treated pertubatively, and recent work has focused on how to include the singular parts of one-pion exchange in the most effective manner [6, 7, 8]" -R. Gilman and F. Gross [3]

"But a principal motivation for using the front-form is that it is a natural choice at very high momentum, where the interactions single out a preferred direction (the beam direction) and the dynamics evolves along the light-front in that direction. The disadvantage is that the generators that contain dynamical quantities ar H_- and J^i, and this means that angular momentum conservation must be treated as a dynamical constraint." -R. Gilman and F. Gross [3]

"Calculations based on quark degrees of freedom must confront the fact that the deuteron is at least a six-quark system. Since the six quarks are identical (because of internal symmetries) the system must be antisymmetrized, and it is not clear that the nucleon should retain its identity in the presence of another nucleon." -R. Gilman and F. Gross [3]

"It is clear that much more work will be needed to clarify the various physics issues, before a convergent scheme is established for treating the e.m. and strong interaction physics properly." -J.A. Tjon [9]

"... there is no clearly correct way to isolate the structure of the nucleon from the structure of the bound state. In model calculations these issues can be handled by separating the problem into two regions: at large separations ($R > R_c$) it is assumed that the system separates into two nucleons interacting through one pion exchange, and at small distances ($R < R_c$) the system is assumed to coalesce into a six-quark bag with all the quarks treated on an equal footing." -R. Gilman and F. Gross [3]

"It turns out that this leading twist pQCD estimate is $10^3 - 10^4$ times smaller than the measured deuteron form factor, implying large soft contributions to the form factor, in agreement with [10, 11], suggesting that pQCD should not be used as an explanation for the form factor. The calculation is extremely complicated and a confirmation, or refutation, is desirable." -R. Gilman and F. Gross [3]

"From the discussions in section 3.8, it is clearly of interest to extend measurements of A to higher Q^2. An ed coincidence experiment is straightforward, but prohibitive timewise with present accelerators. The proposed 12 GeV JLab upgrade allows one to take advantage of the approximate E^2 scaling of σ_M at constant Q^2 and high energy [12]. A large acceptance spectrometer such as MAD would be very helpful. Depending on the details of the upgrade, a one month experiment could provide data to Q^2 of 8 GeV^2." -R. Gilman and F. Gross [3]

"Within the context of a more realistic dynamical theory, one can use response function separations and polarization observables to enhance the sensitivity to various model dependent *unobservables*, such as momentum distributions, meson exchange currents and medium modifications. One strong recent interest has been to choose kinematics in which the unobserved nucleon has a large momentum; the plane wave approximation shows that this configuration enhances sensitivity to initial-state short-range correlations (i.e. the wavefunction) and possibly quark effects. A number of these experiments have been carried out at various accelerators, but no experiments at JLab have yet reported the results." -R. Gilman and F. Gross [3]

"The most precise constraint on these [$I = 1$ exchange] currents comes from the $d \to^1 S_0$ transition, and this part of the trainsition is partly obscured by the poor renergy resolution of the existing high Q^2 measurements. A new and improved experiment at JLab with higher resolution would allow the threshold $d \to^1 S_0$ process to be better extracted, with a better resulting determination of the isovector exchange currents. It is also important to determine whether or not there is a minimum near 1.2 GeV^2." -R. Gilman and F. Gross [3]

"The nucleon-nucleon (NN) interaction has strong tensor forces at long and intermediate distances caused by the pion exchange, which emerges large momentum transfer, and also strong central repulsions at short distance caused by the quark dynamics [13, 14]. It is important to investigate the nuclear structure by treating these characteristics of the NN interaction." -T. Myo [15]

"From those results, only the ^{6}Li ground state show the LS coupling structure and this can be related to the $\alpha + d$ clustering in the $T = 0$ state. ... The detailed analyses including the excited states are performed in our paper [16]." -T. Myo [15]

"SRCs are considered one of the most elusive features of the ground state nuclear wave functions." -M. Sargsian [17]

"One of the methods in probing 2N SRCs is studying high Q^2 inclusive $A(e, e')X$ scattering at $x > 1.4$ in which case virtual photon scatters off the bound nucleon with momenta exceeding $k_F(A)$ [18, 19]." -M. Sargsian [17]

"Another recent news from SRC studies is the observation of a strong (by factor of 20) dominance of pn relative to pp and nn SRC's in the range of the bound nucleon momenta $k_F < p < 600\mathrm{MeV}/c$[20, 21]. This observation of was an indication that at the distances relevant to the above momentum range the NN force is dominated by tensor interaction. This gave a new meaning to the above mentioned ratios:

$$A_2(A) = \frac{2 \cdot \sigma_{eA}}{A \cdot \sigma_{ed}}, \tag{2}$$

which now represent (up to the SRC center of mass motion effect) the probability of finding 2N SRCs in the nucleus A. The observed strong disbalance of pn and pp/nn SRCs allowed also to suggest new approximate relation for the high momentum distribution of protons and neutrons in the nucleus A[22]:

$$n^A_{p/n}(p) = \frac{1}{2x_{p/n}} a_d(A, y) \cdot n_d(p) \tag{3}$$

where $x_{p/n} = \frac{Z}{A}/\frac{A-Z}{A}$ and $y = |1 - 2x_p|$." -M. Sargsian [17]

2 Background and Motivation

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 it's atomic analogue, our understanding of the deuteron remains unsatisfying both experimentally and theoretically.

Through electron scattering on tensor-polarized deuterons, the S- and D-wave states can be disentangled, leading to a fuller understanding of the repulsive nucleon core.

Understanding the nucleon-nucleon potential of the deuteron is essential for understanding short-range correlations. To resolve the short-range structure of nuclei on the level of nucleon and hadronic constituents, we need processes that transfer to the nucleon constituents both energy and momentum larger than the scale of the NN short range correlations. By scanning over a large range of Q^2, we can measure how these processes begin to dominate the tensor asymmetry A_{zz}.

2.1 Tensor Structure of the Deuteron

2.2 Quasi-Elastic and $x > 1$ Scattering from Spin-1 Targets

2.3 The Tensor Asymmetry A_{zz}

3 The Proposed Experiment

3.1 Experimental Method

As in the case for E12-13-011, the measured double differential cross section for a spin-1 target characterized by a vector polarization P_z and tensor polarization P_{zz} is expressed as,

$$\frac{d^2\sigma_p}{d\Omega dE'} = \frac{d^2\sigma_u}{d\Omega dE'}\left(1 - P_z P_B A_1 + \frac{1}{2}P_{zz}A_{zz}\right), \quad (4)$$

where, σ_p (σ_u) 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 polarized tensor asymmetry with $0 < P_{zz} \leq 1$ using an unpolarized electron beam as

$$A_{zz} = \frac{2}{P_{zz}}\left(\frac{\sigma_p}{\sigma_u} - 1\right), \quad (5)$$

where σ_p is the polarized cross section. The tensor polarization is given by

$$P_{zz} = \frac{n_+ - 2n_0 + n_-}{n_+ + n_- + n_0}, \quad (6)$$

where n_m represents the population in the $m_z = +1, -1$, or 0 state.

Eq. 5 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 process, identical to that used for E12-13-011, 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. 5 can be expressed in terms of the charge normalized, efficiency corrected numbers of tensor polarized (N_p) and unpolarized (N_u) counts,

$$A_{zz} = \frac{2}{fP_{zz}}\left(\frac{N_p}{N_u} - 1\right). \quad (7)$$

The dilution factor f corrects for the presence of unpolarized nuclei in the target and is defined by

$$f = \frac{N_D\sigma_D}{N_N\sigma_N + N_D\sigma_D + \Sigma N_A\sigma_A}, \quad (8)$$

Source	Systematic
Polarimetry	9.0%
Dilution/packing fraction	4.0%
Radiative corrections	1.5%
Charge Determination	1.0%
Detector resolution and efficiency	1.0%
Total	10%

Table 1: Estimates of the scale dependent contributions to the systematic error of A_{zz}.

where N_D is the number of deuterium nuclei in the target and σ_D is the corresponding inclusive double differential scattering cross section, N_N is the nitrogen number of scattered nuclei with cross section σ_N, and N_A is the numbers of other scattering nuclei of mass number A with cross section σ_A. The denominator of the dilution factor can be written in terms of the relative volume ratio of ND_3 to LHe in the target cell, otherwise known as the packing fraction p_f. In our case of a cylindrical target cell oriented along the magnetic field, the packing fraction is exactly equivalent to the percentage of the cell length filled with ND_3.

The time necessary to achieve the desired precision δA is:

$$T = \frac{N_T}{R_T} = \frac{16}{P_{zz}^2 f^2 \delta A_{zz}^2 R_T} \tag{9}$$

where R_T is the total rate and $N_T = N_p + N_u$ is the total estimated number of counts to achieve the uncertainty δA_{zz}.

3.1.1 Statistical Uncertainty

To investigate the statistical uncertainty we start with the equation for A_{zz} using measured counts for polarized data (N_p) and unpolarized data (N_u),

$$A_{zz} = \frac{2}{f P_{zz}} \left(\frac{N_p}{N_u} - 1 \right). \tag{10}$$

The statistical error with respect to counts is then

$$\delta A_{zz} = \frac{2}{f P_{zz}} \sqrt{\left(\frac{\delta N_p}{N_u} \right)^2 + \left(\frac{N_p \delta N_u}{N_u^2} \right)^2}. \tag{11}$$

3.1.2 Systematic Uncertainty

Table 1 shows a list of the scale dependent uncertainties contributing to the systematic error in A_{zz}.

With careful minimization, the uncertainty in P_z can be held to better than 4%, as demonstrated in the recent g2p/GEp experiment [23]. This leads to a a relative uncertainty in P_{zz} of 7.7%.

Alternatively, the tensor asymmetry can be directly extracted from the NMR lineshape as discussed in Sec. **??**, with similar uncertainty. The uncertainty from the dilution factor and packing fraction of the ammonia target contributes at the 4% level. The systematic effect on A_{zz} due to the QED radiative corrections will be quite small. For our measurement there will be no polarized radiative corrections at the lepton vertex, and the unpolarized corrections are known to better than 1.5%.

Charge calibration and detector efficiencies are expected to be known better to 1%, but the impact of time-dependent drifts in these quantities must be carefully controlled.

Time dependent factors

Eq. 7 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. To investigate the systematic differences in the time dependent components of the integrated counts, we need to consider the effects from calibration, efficiency, acceptance, and luminosity between the two polarization states.

Fluctuations in luminosity due to target density variation can easily be kept to a minimum by keeping the material beads at the same temperature for both polarization states by control of the microwave and the LHe evaporation. The He vapor pressure reading can give accuracy of material temperature changes at the level of $\sim$0.1%. Beam rastering can also be controlled to a high degree.

The acceptance of each cup can only change as a function of time if the magnetic field changes. The capacity to set and reset and hold, set-ability, the target supper conducting magnet to a desired holding field is $\delta B/B$ =0.01%. This implies that like the cup length l and the acceptance $\mathcal{A}$ for each polarization states is the same.

In order to look at the effect on A_{zz} due to drifts in beam current measurement calibration and detector efficiency we rewrite Eq. 7 explicitly in terms of the raw measured counts N_1 and N,

$$\begin{aligned} A_{zz} &= \frac{2}{fP_{zz}}\left(\frac{N_1^c}{N^c}-1\right) \\ &= \frac{2}{fP_{zz}}\left(\frac{Q\varepsilon l\mathcal{A}}{Q_1\varepsilon_1 l\mathcal{A}}\frac{N^1}{N}-1\right) \end{aligned} \tag{12}$$

where Q represents the accumulated charge, and ε is the detector efficiency. The target length l and acceptance $\mathcal{A}$ are identical in both states to first order.

We can then express Q_1 as the change in beam current measurement calibration that occurs in the time it takes to collect data in one polarization state before switching such that $Q_1 = Q(1-dQ)$. In this notation dQ is a dimensionless ratio of changes in different polarization states. A similar representation is used for drifts in detector efficiency leading to,

$$A_{zz} = \frac{2}{fP_{zz}}\left(\frac{N_1 Q(1-dQ)\varepsilon(1-d\varepsilon)}{NQ\varepsilon}-1\right). \tag{13}$$

which leads to,

$$A_{zz} = \frac{2}{fP_{zz}}\left(\frac{N_1}{N}(1-dQ-d\varepsilon+dQd\varepsilon)-1\right). \tag{14}$$

For estimates of the dQ and $d\varepsilon$ we turn to previous experimental studies. For HRS detector drift during JLab transversity experiment E06-010, the detector response was measured such that the normalized yield for same condition over a three month period indicated little change ($< 1\%$). These measurement where then use to show that for short time (20 minutes periods between target spin flip), the detector drift is estimated to be less than 1% times the ratio of the time period between target spin flip and three months. For the present experiment we use the same estimate except for the period between target polarization states used is $\sim$12 hours leading to an overall drift $d\varepsilon \sim 0.01\%$. A similar approach can be used to establish an estimate for dQ using studies from the data from the (g2p/GEp) experiment resulting in $d\varepsilon \sim 0.01\%$.

To express A_{zz} in terms of the estimated experimental drifts in efficiency and current measurement we can write,

$$A_{zz} = \frac{2}{fP_{zz}}\left(\frac{N_1}{N} - 1\right) \pm \frac{2}{fP_{zz}} d\xi. \tag{15}$$

This leads to a contribution to A_{zz} on the order of $1 \times 10^{-}3$,

$$dA_{zz}^{drift} = \pm \frac{2}{fP_{zz}} d\xi = \pm 3.7 \times 10^{-3}. \tag{16}$$

Though a very important contribution to the error this value allows a clean measurement of $A_{zz} = 0$ at $x = 0.45$ without overlap with the Hermes error bar. For this estimate we assume only two polarization state changes in a day. If it is possible to increase this rate then the systematic effect in A_{zz} also decreases accordingly.

Naturally detector efficiency can drift for a variety of reasons, for example including fluctuations in gas quality, HV drift or drifts in the spectrometers magnetic field. All of these types of variation as can be realized both during the experiment though monitoring as well as systematic studies of the data collected.

There can be difficult to know changes in luminosity however the identical condition of the two polarization states minimizes the relative changes in time. There are also checks on the consistency of the cross section data that can be use ensuring the quality of each run used in the asymmetry analysis.

4 Summary

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