

Measurement of the Tensor Asymmetry A_{zz} from $0.3 < x < 1.9$ and Elastic T_{20}

A Proposal to Jefferson Lab PAC 43
(Update to LOI12-14-002)

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Abstract

In this update to LOI12-14-002, we propose the first measurement of the tensor asymmetry A_{zz} in the quasi-elastic region through the tensor polarized $D(e, e')X$ channel; an asymmetry that is sensitive to the nucleon-nucleon potential. Previous measurements of A_{zz} have been used to extract b_1 in the DIS region and T_{20} in the elastic region. In the quasi-elastic region, A_{zz} data will be used to compare light cone calculations with variation nucleon-nucleon calculations, and is an important quantity to determine for understanding tensor effects, such as the dominance of pn correlations in nuclei.

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 and M. Strikman 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] and can be discriminated experimentally at the $3 - 6\sigma$ level. Additionally, the calculations were done using multiple deuteron wavefunctions which show a large discrepancy at high x .

Additionally, our measurement of A_{zz} allows for a simultaneous measurement of the tensor analyzing power T_{20} without any further beam time or equipment by making a kinematic cut on the elastic peak. The lowest Q^2 measurement will fall on the most experimentally probed and theoretically understood region, making it ideal for ensuring that the tensor polarized target is operating correctly and to help reduce target systematic uncertainty, the leading systematic in this experiment. At medium Q^2 , our measurement will fall in the same region where there is currently a discrepancy between Hall A and Hall C results. Our final point will lie at the highest Q^2 value ever measured for T_{20} , and will test whether the observable continues on a plateau. These measurements of T_{20} will also cover the largest range in Q^2 measured by a single experiment.

We propose an experimental determination of A_{zz} and T_{20} utilizing the same equipment as the E13-12-011 b_1 experiment. Three different Q^2 values will be measured over the course of 34 days, with 10.3 additional days of overhead. The measurements are less sensitive to systematic uncertainties than E13-12-011, so this experiment would be utilized in parallel to better understand the in-beam conditions and time-dependent systematic effects of a tensor polarized target for the b_1 experiment.

Additionally, the kinematic requirements of A_{zz} also allow for the simultaneous measurement of T_{20} at multiple Q^2 points ranging from $0.13 < Q^2 < 1.8 \text{ GeV}^2$, the largest range of a single experiment. At low $Q^2 \sim 0.2 \text{ GeV}^2$, T_{20} is well known experimentally and theoretically making it an ideal calibration point to reduce systematics from target polarization. At mid $Q^2 \sim 0.7 \text{ GeV}^2$, we will take a measurement in the region where previous JLab Hall C results disagree with results from Bates. Finally, at high $Q^2 \sim 1.5$ and 1.8 GeV^2 we will measure T_{20} at the largest momentum transfer yet, further constraining calculations at high Q^2 .

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1 A_{zz} Background

The deuteron is the simplest composite 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. Our experimental and theoretical understanding of the deuteron remains unsatisfying.

Due to their small size and simple structure, tensor polarized deuterons are ideal for studying nucleon-nucleon interactions. Tensor polarization enhances the D-state contribution, which compresses the deuteron [3], making the system more sensitive to short-range QCD effects. Understanding the nucleon-nucleon potential of the deuteron is essential for understanding short-range correlations as they are largely dependent on the tensor force [4]. We can resolve the short-range structure of nuclei on the level of nucleon and hadronic constituents by utilizing processes that transfer to the nucleon constituents both energy and momentum larger than the scale of the NN short-range correlations, particularly at $Q^2 > 1 \text{ (GeV/c)}^2$.

By taking a ratio of cross sections from electron scattering from tensor-polarized and unpolarized deuterons, the S and D-wave states can be disentangled, leading to a fuller understanding of the repulsive nucleon core. A measurement of A_{zz} is sensitive to the $\frac{D^2-SD}{S^2+D^2}$ ratio and its evolution with increasing minimal momentum of the struck nucleon. Originally calculated by L. Frankfurt and M. Strikman [1], this has recently been revisited by M. Sargsian, who calculated A_{zz} in this region using a light cone approach and a virtual nucleon approach. The calculations vary by up to a factor of 2, and can be experimentally determined at the $3 - 6\sigma$ level as discussed in this letter.

For the lower Q^2 region, W. Van Orden has calculations in progress using different nucleon-nucleon potentials, as well as different prescriptions for handling the reactions mechanisms [5]. Similar calculations are currently being finalized for the approved $D(e, e'p)n$ at high Q^2 , high p_m experiment. Once completed, he will turn his attention to tensor polarization observables in the low Q^2 region.

Additionally, measuring A_{zz} in the quasi-elastic region will fill a gap in measurements performed on tensor polarized deuterium. It is directly proportional to the observable used in the elastic region to measure T_{20} , by $A_{zz} \propto T_{20}$. Due to the large acceptance of the SHMS spectrometer, we will be taking data in the $x = 2$ elastic range as well that, at low Q^2 , may be able to resolve the discrepancy of the deuteron structure functions that were measured at JLab in Halls A and C [6]. This will be investigated further as a potential parasitic measurement when the full proposal is submitted. In the deep inelastic region, A_{zz} will soon be measured to extract the tensor structure function b_1 by the relation $A_{zz} \propto \frac{b_1}{F_1^D}$. Not only will measuring A_{zz} in the quasi-elastic region provide information necessary for understanding the properties of the deuteron and contribution from the tensor force, but it will be the first experiment to bridge a gap in measurements of electron scattering from tensor-polarized deuterons.

1.1 Probing the Deuteron Wavefunction

It was suggested for some time [7] that to resolve the microscopic structure of nuclei one needs to study scattering at sufficiently large momentum transfer and large relative momenta of the produced nucleons. This logic was confirmed [4] by a series of experiments at SLAC [8] and

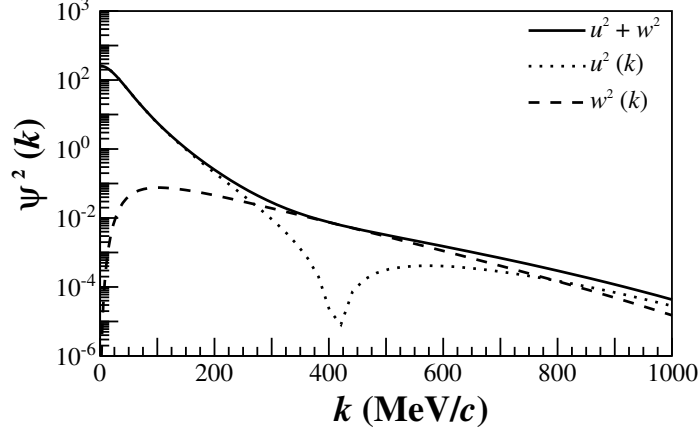


Figure 1: The AV18 [11] deuteron wave-function, showing the dominance of the D-state (dashed) in comparison to the S-state (dotted) in the full wavefunction (solid) at high momentum ($k > 300$ MeV/c).

JLab [9, 10] that directly observed short-range correlations (SRC) in a series of nuclei, and established a similar effect of SRC in the deuteron and in heavier nuclei with pn correlations giving the dominant contribution. Hence, the deuteron serves as a “hydrogen atom” for the studies of the microscopic short-range structure of the nuclei since it is the simplest nuclei that follows SRC scaling.

To achieve further progress, it is necessary to improve our knowledge of the deuteron wave function at high momenta, and to separate the S and D contributions to the high momentum component of the deuteron. The dominance of the D-wave at a large range of the nucleon momenta is expected in a range of the theoretical models, as demonstrated in Fig. 1, but experimentally it was probed in a rather indirect way via measurement of T_{20} for the deuteron form factor [6]. Still, the knowledge of S/D ratio for large momenta is rather poor. Indeed, all wavefunctions are constrained by low energy data to reproduce the S/D ratio at small momenta while the overall probability of the D-wave in the deuteron differs by a factor up to 1.5, leading to a large difference of the S/D ratio at large momenta.

The S and D-states are related to the tensor asymmetry A_{zz} by [1]

$$A_{zz} \propto \frac{\frac{1}{2}w^2(k) - u(k)w(k)\sqrt{2}}{u^2(k) + w^2(k)}, \quad (1)$$

where $u(k)$ is the S-state wave function and $w(k)$ is the D-state wave function. Additionally, measuring A_{zz} at lower Q^2 will map out the transition from hadronic to partonic degrees of freedom.

Ratios of inclusive cross sections at $x > 1$ has demonstrated an early onset of the scaling of the ratios when plotted as a function of the light-cone fraction of the struck nucleon momentum. As a result, the ratios provide a direct measurement of the ratio of the high momentum components in nuclei. Similarly, one can expect that in the case of scattering from the polarized deuteron we expect the early scaling for the asymmetry when plotted as a function of the minimal struck

nucleon momentum or the light cone fraction in the $A(e, e')$ case. It was observed at JLab that the scaling of the ratios set in starting at $Q^2 \sim 1 \text{ GeV}^2$ [9] so covering the range of Q^2 up to 2 GeV^2 will be sufficient to measure the S/D ratios in an interesting momentum range.

It is worth noting here that in addition to comparing predictions for the different wave functions, one expects to be able to distinguish between non-relativistic and light cone quantum mechanic models. The principal difference between the models is the relation between the spectator momentum and momentum in the wave function. In the nonrelativistic model they coincide, while in the light cone model the relation is non-linear starting at $k \sim 250 \text{ MeV}/c$. This difference is most clearly manifested in the scattering from the polarized deuteron due to a strong dependence of the S/D ratio on the nucleon momentum.

1.2 Study of the Relativistic NN Bound System

One of the important issues in studying of nuclear structure at short distances is the relativistic description of the bound system. This is an important issue also in understanding the QCD medium effect with recent studies indicating that parton distribution modifications in nuclei are proportional to the high momentum component of nuclear wave function.

The deuteron is the simplest bound system and naturally any self-consistent attempt to understand the relativistic effects in the bound nuclear systems should start with the deuteron. The issue of the relativistic description of the deuteron has long history with extensive research that started in late 1970's [12, 13, 14, 7].

The experimental studies of the relativistic effects in the deuteron up to now include the large Q^2 elastic ed scattering [15], however due to complexities in the reaction mechanism [16] the relativistic effects were difficult to isolate.

The inclusive $D(e, e')X$ experiments from tensor-polarized deuterons at $Q^2 > 1 \text{ GeV}^2$ and $x > 1$ region gives a new possibility to probe the relativistic structure of the deuteron. In this case the use of the tensor polarized deuteron allows us to prepare the nucleus in the most compact state in which, due to the absence of the pure S-wave² contribution, the system in average is sensitive to the higher moment of the nucleon in the deuteron. At large $Q^2 > 1 \text{ GeV}^2$ kinematics, the probed longitudinal momenta of the bound nucleon $p_z \approx m_N(1 - x)$, or the light cone momentum fraction $\alpha \geq x$. Because of these kinematic conditions and the absence of the large S-wave² contribution, one expects a measurable relativistic effects already at $x \leq 1.2$.

The biggest advantage is that one expects less uncertainty due to the choice of the NN potential and reaction dynamics due to relatively small values of the bound nucleon momenta involved ($\geq 200 \text{ MeV}/c$).

The sensitivity to relativistic effects is estimated using the theoretical calculations based on two very different approaches. The first approach treats the virtuality of the bound nucleon within a description of the deuteron in the lab. frame with treating the interacting nucleon as being virtual (virtual nucleon, or VN, approximation) by taking the residue over the energy of the spectator nucleon. In this case, the deuteron wave function satisfies the covariant equation of two-nucleon bound system with spectator being on energy shell [17, 18].

Another approach is based on the observation that high energy processes evolve along the light-cone (LC). Therefore, it is natural to describe the reaction within the light-cone non-covariant

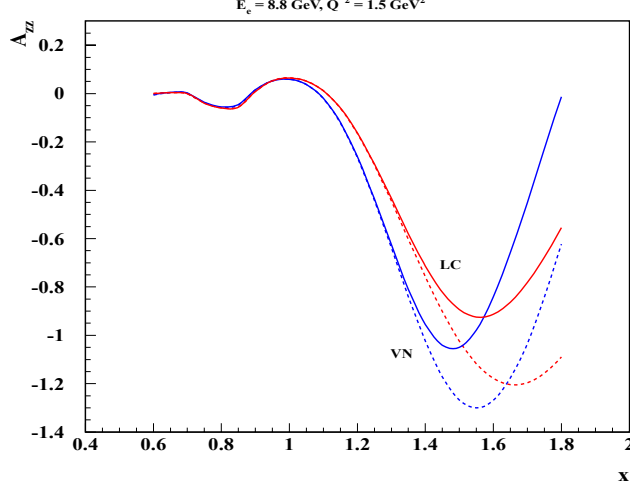


Figure 2: The A_{zz} observable calculated at $Q^2 = 1.5 \text{ (GeV/c)}^2$ using the light-cone (red) and virtual nucleon (blue) models with NN potential inputs of AV18 (solid) and CDBonn (dotted). Calculations provided by M. Sargsian and M. Strikman [19].

framework [7]. Negative energy states do not enter in this case, though one has to take into account so called instantaneous interactions. In the approximation when non-nucleonic degrees of freedom in the deuteron wave function can be neglected, one can unambiguously relate the light-cone wave functions to those calculated in the lab. frame by introducing the LC pn relative three momentum,

$$k = \sqrt{\frac{m^2 + p_t^2}{\alpha(2 - \alpha)}} - m^2. \quad (2)$$

In Fig. 2, the prediction for VN [17] and LC [8] approximations are given for the highest Q^2 kinematics proposed. As was previously mentioned, a measurable difference is predicted to be observable already at $x \geq 1.2$. to the choice of the wave function.

1.3 Interest from Theorists

The measurement proposed in this letter has stirred interest in a number of theorists who are working on calculations. Many of these are on-going and are expected to be completed in the coming months to further the physics motivation of a measurement of A_{zz} in the quasi-elastic region at various momentum-transfer.

The light cone and virtual nucleon calculations of M. Sargsian [20] and M. Strikman [21] are already available for A_{zz} and are presented in this document. Early calculations of the M. Strikman light-cone model indicate a potential measurable discrepancy based on the input of different NN potentials, but the results are very preliminary and require further investigation. S. Liuti has agreed to join in this theoretical effort, stating “This is an important measurement to know, and should be calculated more thoroughly.” [22]

Models involving 6-quark calculations of quasi-elastic A_{zz} can be calculated by G. Miller [23] and have been motivated by the collaboration. In his own words, he states “This measurement was a highlighted need early at JLab. A new measurement at higher Q^2 would be very interesting. In principle such could test my model. I could calculate the influence of my 6-quark configurations on elastic scattering.”

Continuing his interest from DIS b_1 calculations, W. Cosyn is developing calculations of the quasi-elastic contribution to inclusive deuteron scattering, which will be the dominant contribution in the $x > 1$ regime [24]. His calculations, which include final-state interactions, can be modified to include A_{zz} and expects to have them within the coming months. In his words, “I hope to do some calculations soon and could easily do them for the kinematics in your proposal.”

In addition, W. Van Orden has calculations in progress using different nucleon-nucleon potentials, as well as different prescriptions for handling the reactions mechanisms [5]. Similar calculations are currently being finalized for the approved $D(e, e'p)n$ at high Q^2 , high p_m experiment. Once completed, he will turn his attention to tensor polarization observables in the low Q^2 region and investigate the effects from differing NN potentials.

In summary, we are encouraged that several theorists have begun serious efforts to calculate A_{zz} in the $x > 1$ region using a variety of models. We anticipate that the PAC’s guidance will further encourage and focus these efforts.

2 T_{20} Background

For the following discussion we use the nomenclature described by the Madison Convention [25].

3 The Proposed Experiment

We propose to measure the tensor asymmetry A_{zz} and tensor analyzing power T_{20} from inclusive electron scattering from polarized deuterons in the quasi-elastic and elastic region of $0.30 < x < 2.0$, $0.2 \text{ (GeV/c)}^2 < Q^2 < 2.9 \text{ (GeV/c)}^2$, and $1.8 < W_{NN} < 3.1 \text{ GeV}$ using the Hall C HMS and SHMS spectrometers at forward angle using a solid polarized ND_3 target.

3.1 A_{zz} Experimental Method

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

$$\frac{d^2\sigma_p}{d\Omega dE'} = \frac{d^2\sigma_u}{d\Omega dE'} \left(1 - P_z P_B A_1 + \frac{1}{2} P_{zz} A_{zz} \right), \quad (3)$$

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 positive tensor polarization using an

243 unpolarized electron beam as

$$A_{zz} = \frac{2}{P_{zz}} \left(\frac{\sigma_p - \sigma_u}{\sigma_u} \right). \quad (4)$$

244 The tensor polarization is given by

$$P_{zz} = \frac{n_+ - 2n_0 + n_-}{n_+ + n_- + n_0}, \quad (5)$$

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

246 Eq. 4 reveals that the asymmetry A_{zz} compares two different cross sections measured under
 247 different polarization conditions of the target: positively tensor polarized and unpolarized. To
 248 obtain the relative cross section measurement in the same configuration, the same target cup and
 249 material will be used at alternating polarization states (polarized vs. unpolarized), and the magnetic
 250 field providing the quantization axis will be oriented along the beamline at all times. This field will
 251 always be held at the same value, regardless of the target material polarization state. This process,
 252 identical to that used for the E12-13-011 b_1 measurement, ensures that the acceptance remains
 253 consistent within the stability (10^{-4}) of the super conducting magnet.

254 Since many of the factors involved in the cross sections cancel in the ratio, Eq. 4 can be
 255 expressed in terms of the charge normalized, efficiency corrected numbers of tensor polarized
 256 (N_p) and unpolarized (N_u) counts,

$$A_{zz} = \frac{2}{fP_{zz}} \left(\frac{N_p - N_u}{N_u} \right). \quad (6)$$

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

$$f = \frac{N_D \sigma_D}{N_N \sigma_N + N_D \sigma_D + \sum_A N_A \sigma_A}, \quad (7)$$

259 where N_D is the number of deuterium nuclei in the target and σ_D is the corresponding inclusive
 260 double differential scattering cross section, N_N is the nitrogen number of scattered nuclei with
 261 cross section σ_N , and N_A is the number of other scattering nuclei of mass number A with cross
 262 section σ_A . As has been noted in previous work [1], the dilution factor at high x drops off consider-
 263 ably until the SRC plateau region, as shown in Fig. 3. By using a high-luminosity solid target and
 264 a low scattering angle θ_e , this effect will be counteracted. The dilution factor is a much smaller
 265 problem for elastic scattering at $x = 2$.

266 The dilution factor can be written in terms of the relative volume ratio of ND_3 to LHe in the
 267 target cell, otherwise known as the packing fraction p_f . In our case of a cylindrical target cell
 268 oriented along the magnetic field, the packing fraction is exactly equivalent to the percentage of the
 269 cell length filled with ND_3 .

270 If the time is evenly split between scattering off of polarized and unpolarized ND_3 , the time
 271 necessary to achieve the desired precision δA is:

$$T = \frac{N_p}{R_p} + \frac{N_u}{R_u} = \frac{8}{f^2 P_{zz}^2} \left(\frac{R_p(R_u + R_p)}{R_u^3} \right) \frac{1}{\delta A_{zz}^2} \quad (8)$$

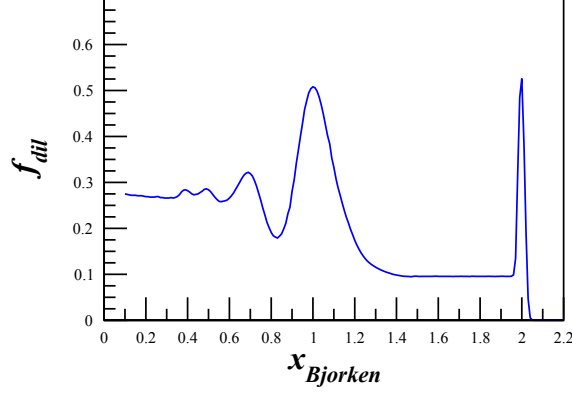


Figure 3: The estimated dilution factor, in this case at $Q^2 = 1.5 \text{ (GeV/c)}^2$, is expected to drop off at high x until it reaches the SRC plateau region and then the elastic peak at $x = 2$. The low dilution factor of $1.1 < x < 1.95$ will be counteracted by using a high-luminosity target.

where $R_{p(u)}$ is the polarized (unpolarized) rate and $N_{p(u)}$ is the total estimated number of polarized (unpolarized) counts to achieve the uncertainty δA_{zz} .

3.2 T_{20} Experimental Method

A measurement of T_{20} will be extracted from A_{zz} on the elastic peak for each Q^2 mentioned in Section 3.3. We will follow a similar method to B. Boden *et al* [26], which also measured T_{20} using a tensor polarized target. Our methods differ only in that we will use the high resolution of the HMS and SHMS to determine the elastic peak through kinematic cuts, where Boden utilized a second spectrometer for that purpose.

Boden describes the relationship between the measured ratio of unpolarized and tensor-polarized yields and T_{20} in the following manner. They start with the experimental ratio R_{exp} between the tensor polarized and unpolarized states,

$$R_{exp} = \frac{d\sigma_p}{d\sigma_u} = 1 + P_{zz} \left(\frac{d\sigma_T - d\sigma_u}{d\sigma_u} \right) = 1 + P_{zz} (R_T - 1) \quad (9)$$

$$R_T - 1 = \frac{1}{P_{zz}} \left(\frac{d\sigma_p}{d\sigma_u} - 1 \right). \quad (10)$$

This matches closely to our definition of A_{zz} ,

$$A_{zz} = \frac{2}{f P_{zz}} \left(\frac{d\sigma_p}{d\sigma_u} - 1 \right), \quad (11)$$

where the dilution factor would be $f = 1$ in the Boden extraction, since they are tagging deuterons and have negligible contamination from other sources.

Thus, R_T and A_{zz} are related by

		E_0 (GeV)	Q^2 (GeV ²)	E' (GeV)	$\theta_{e'}$ (°)	Rates (kHz)	PAC Time (Days)
SHMS	(S1)	8.8	1.5	8.36	8.2	0.38	25
HMS	(H1)	8.8	2.9	7.26	12.2	0.04	25
SHMS	(S2)	6.6	0.7	6.35	7.5	3.57	8
HMS	(H2)	6.6	1.8	5.96	12.3	0.09	8
SHMS	(S3)	2.2	0.2	2.15	10.9	10.5	1
HMS	(H3)	2.2	0.3	2.11	14.9	3.23	1

Table 1: Summary of the central kinematics and physics rates using the Hall C spectrometers.

$$R_T - 1 = \frac{1}{2}A_{zz}. \quad (12)$$

Utilizing forward electron scattering to reduce magnetic contributions to a negligible amount, $(R_T - 1)$ is related to T_{20} by

$$T_{20} = -\sqrt{8}(R_T - 1), \quad (13)$$

which we can use to relate T_{20} to an elastic measurement of A_{zz} by

$$T_{20} = -\sqrt{2}A_{zz}. \quad (14)$$

3.3 Kinematics

We propose to measure the tensor asymmetry A_{zz} for $0.30 < x < 2.0$, $0.2 \text{ (GeV}/c)^2 < Q^2 < 2.9 \text{ (GeV}/c)^2$, and $1.8 < W_{NN} < 3.1 \text{ GeV}$ and extract the tensor analyzing power T_{20} for $0.2 \text{ (GeV}/c)^2 < Q^2 < 1.8 \text{ (GeV}/c)^2$. Central kinematics of the spectrometers are given in Table 1. Fig. 4 shows the planned kinematic coverage utilizing the Hall C HMS and SHMS spectrometers at forward angles.

The polarized ND₃ target is discussed in Section 3.5. 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. The tensor polarization and packing fraction used in the rates estimate are 30% and 0.65, respectively. The dilution factor in the range of this measurement is shown in Fig. 5. The spread of the elastic peak for the dilution factor was calculated assuming a momentum resolution of 0.1% for the HMS and 0.08% for the SHMS. With an incident electron beam current of 80 nA, the expected deuteron luminosity is $1.2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$.

The momentum bite and the acceptance were assumed to be $\Delta P = \pm 8\%$ and $\Delta\Omega = 5.6 \text{ msr}$ for the HMS, and $\Delta P = {}^{+20\%}_{-8\%}$ and $\Delta\Omega = 4.4 \text{ msr}$ for the SHMS. For the choice of the kinematics, special attention was taken onto the angular and momentum limits of the spectrometers with a longitudinal polarized target: for the HMS, $12.2^\circ \leq \theta \leq 85^\circ$ and $1 \leq P_0 \leq 7.3 \text{ GeV}/c$, and for

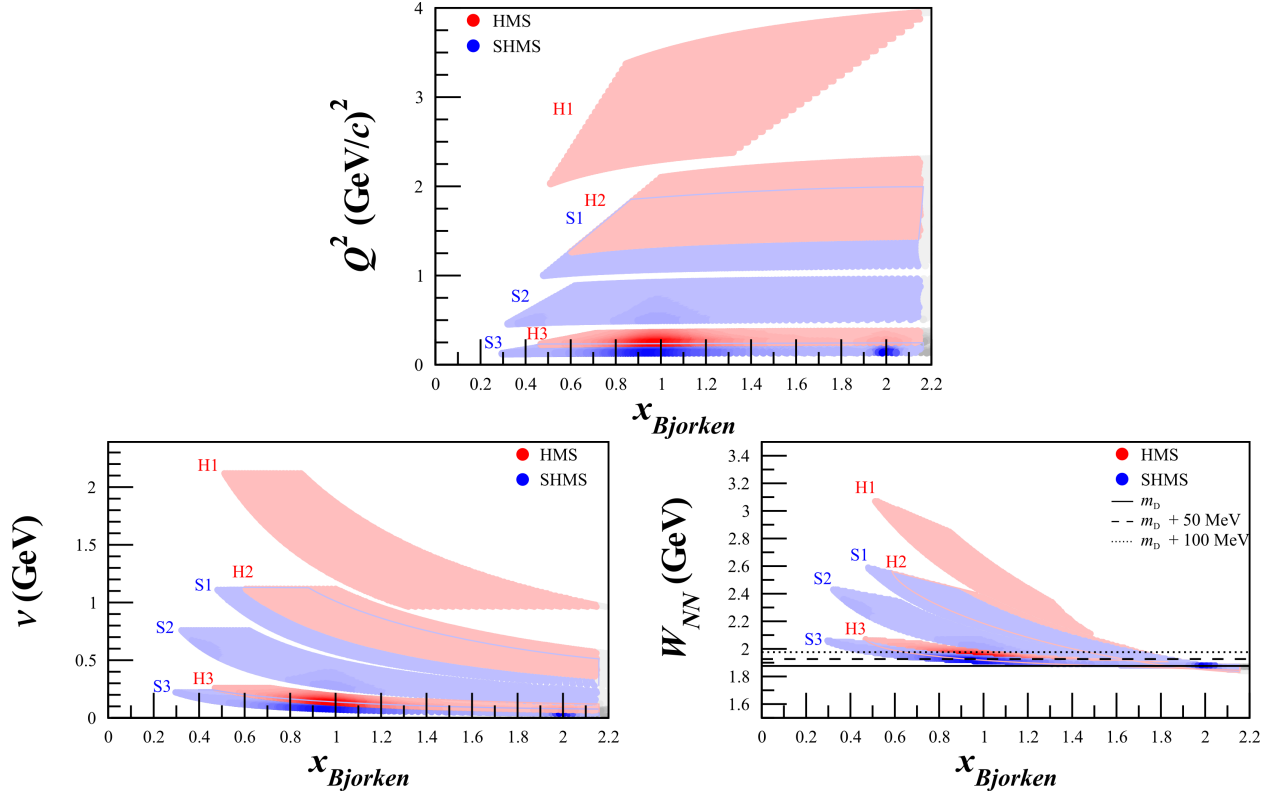


Figure 4: Kinematic coverage for central spectrometer settings at $Q^2 = 2.9$ (GeV/c)² (H1), 1.8 (GeV/c)² (H2), 1.5 (GeV/c)² (S1), 0.7 (GeV/c)² (S2), 0.3 (GeV/c)² (H3), and 0.2 (GeV/c)² (S3). The grey regions are not included in our statistics estimates since they fall outside the range of electron-deuteron scattering. Darker shading represents areas with higher statistics. The solid, dashed, and dotted lines in the W_{NN} plot indicate deuteron mass, deuteron mass + 50 MeV, and deuteron mass + 100 MeV, respectively. Virtual-nucleon and light cone calculations are only valid for $W_{NN} > m_D + 50$ MeV.

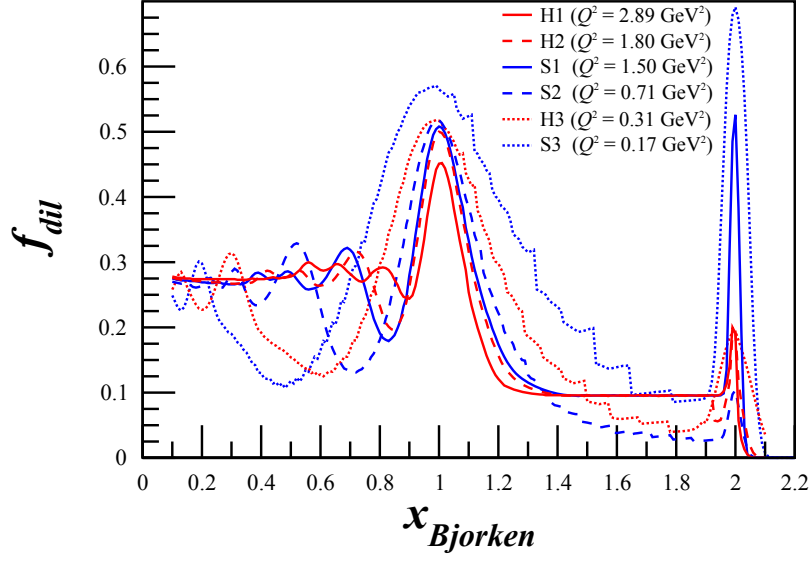


Figure 5: Projected dilution factor covering the entire x range to be measured using a combination of P. Bosted's [27] and M. Sargsian's [20] code, along with a calculation of the elastic peak using a parametrization of the deuteron form factors, for the SHMS and HMS.

the SHMS, $5.5^\circ \leq \theta \leq 40^\circ$ and $2 \leq P_0 \leq 11$ GeV/c. In addition, the opening angle between the spectrometers is physically constrained to be larger than 17.5° .

A total of 34 days of beam time is requested for production data, with an additional 10.3 days of expected overhead. The expected uncertainties, described in detail in Section 3.4, are given in Tables 2-4 and Figs. 6-8.

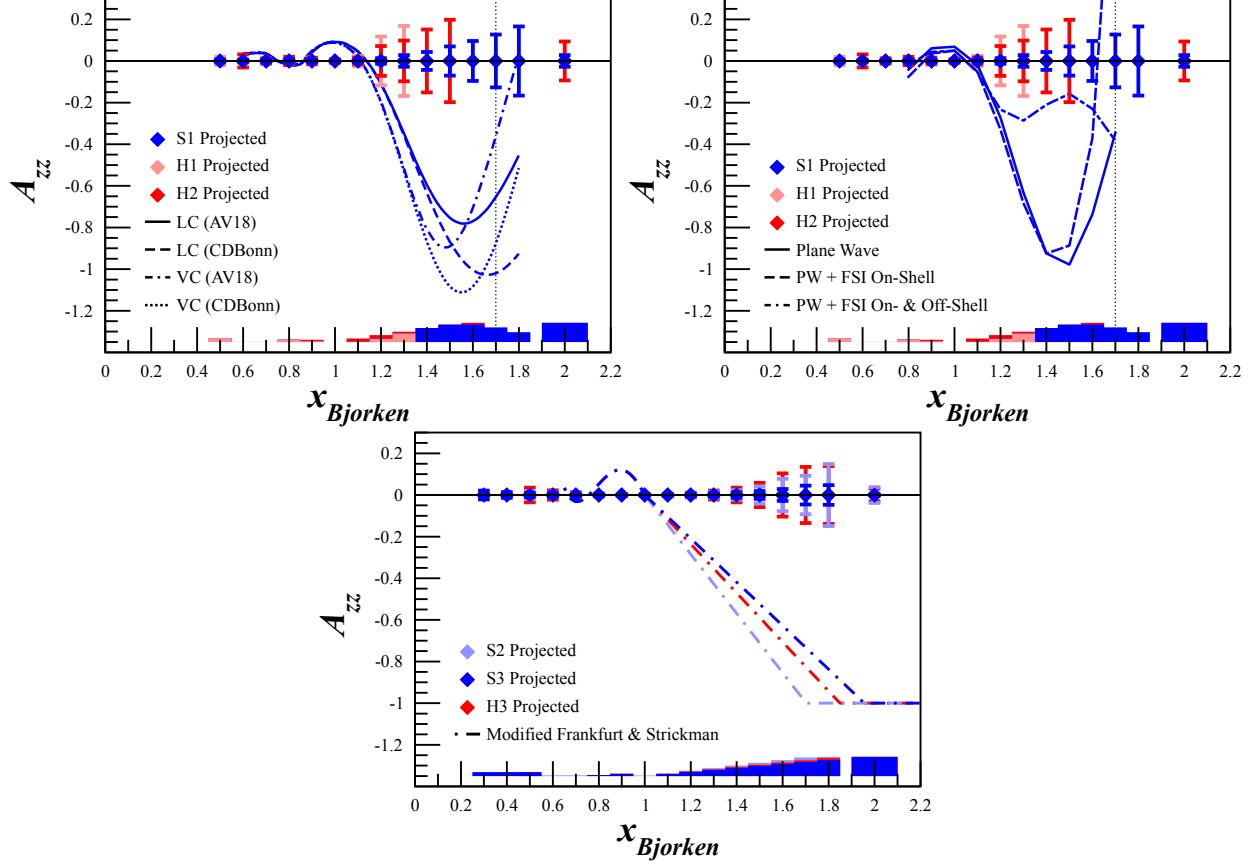


Figure 6: Projected uncertainties for the tensor asymmetry A_{zz} with 34 days of beam time. The band represents the systematic uncertainty. The top row shows the $Q^2 > 1.0 \text{ (GeV/c)}^2$ settings and the bottom row shows the $Q^2 < 1.0 \text{ (GeV/c)}^2$. The upper x limit for H1 (H2) is $x = 1.3$ ($x = 1.5$). The upper-left plot includes light-cone (LC) and virtual-nucleon (VN) calculations provided by M. Sargsian [19], as well as the dependence of each model on various deuteron wave functions (AV18, CDBonn). The dotted line at $x = 1.75$ indicates the threshold of $W_{NN} > m_D + 100 \text{ MeV}$ where LC and VN calculations begin to not be valid as A_{zz} approaches the elastic peak [8]. The upper-right plot includes virtual-nucleon plane wave and final state interaction (FSI) calculations provided by W. Cosyn [24]. The bottom row includes a modified Frankfurt and Strickman model [1] that estimates the peak shifts in x expected due to the SRC scaling changing with Q^2 [28].

	H1: $Q^2 = 2.9 \text{ (GeV/c)}^2$			H2: $Q^2 = 1.8 \text{ (GeV/c)}^2$			S1: $Q^2 = 1.5 \text{ (GeV/c)}^2$		
x	f_{dil}	$\delta A_{zz}^{stat} \times 10^{-2}$	$\delta A_{zz}^{sys} \times 10^{-2}$	f_{dil}	$\delta A_{zz}^{stat} \times 10^{-2}$	$\delta A_{zz}^{sys} \times 10^{-2}$	f_{dil}	$\delta A_{zz}^{stat} \times 10^{-2}$	$\delta A_{zz}^{sys} \times 10^{-2}$
0.50	0.29	2.02	1.84	—	—	—	0.25	0.72	1.84
0.60	0.29	0.91	????	0.27	3.15	????	0.30	0.36	????
0.70	0.27	1.01	????	0.32	1.26	????	0.29	0.38	????
0.80	0.30	1.11	1.34	0.20	2.00	0.48	0.17	0.74	1.34
0.90	0.24	1.73	0.38	0.27	1.45	1.10	0.29	0.44	0.38
1.00	0.46	1.03	????	0.50	0.74	????	0.51	0.24	????
1.10	0.28	2.48	0.14	0.33	1.58	1.65	0.34	0.49	0.14
1.20	0.09	11.7	1.55	0.10	7.18	3.31	0.17	1.34	1.55
1.30	0.11	16.8	4.13	0.11	9.76	4.96	0.12	2.79	4.13
1.40	—	—	—	0.12	15.1	6.65	0.13	4.30	6.72
1.50	—	—	—	0.11	19.8	8.29	0.10	7.01	8.34
1.60	—	—	—	—	—	—	0.10	9.60	8.42
1.70	—	—	—	—	—	—	0.10	12.7	7.04
1.80	—	—	—	—	—	—	0.10	16.6	4.72
2.00	—	—	—	0.20	9.33	9.20	0.50	2.79	9.20

Table 2: Summary of the expected uncertainty for each x bin for settings S1, H1, and H2.

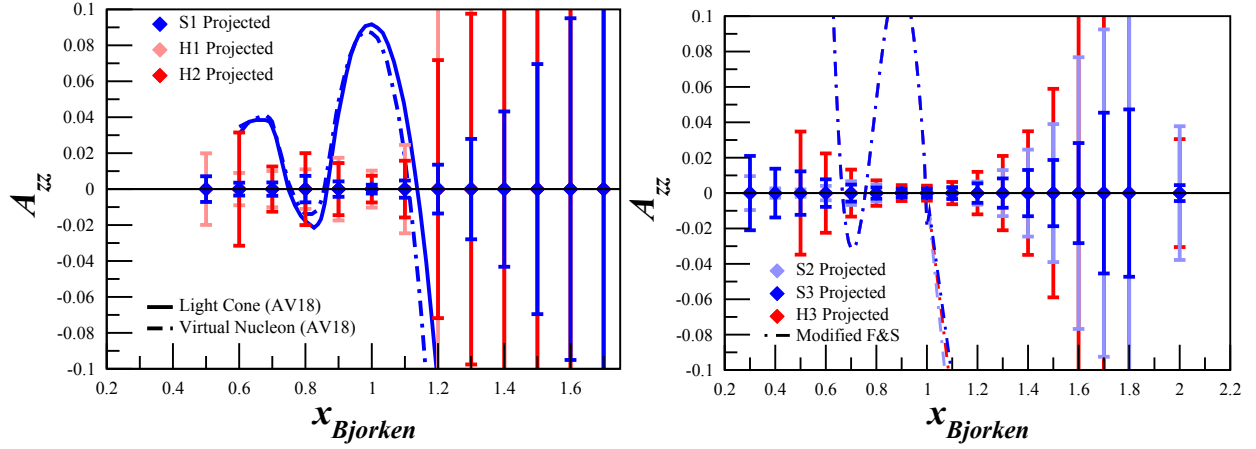


Figure 7: Projected uncertainties for the tensor asymmetry A_{zz} with 34 days of beam time, same as in Figure 6, but zoomed in to $-0.1 < A_{zz} < 0.1$ to more clearly show the small uncertainties around the quasi-elastic peak.

x	S2: $Q^2 = 0.7 \text{ (GeV/c)}^2$			H3: $Q^2 = 0.3 \text{ (GeV/c)}^2$			S3: $Q^2 = 0.2 \text{ (GeV/c)}^2$		
	f_{dil}	δA_{zz}^{stat} $\times 10^{-2}$	δA_{zz}^{sys} $\times 10^{-2}$	f_{dil}	δA_{zz}^{stat} $\times 10^{-2}$	δA_{zz}^{sys} $\times 10^{-2}$	f_{dil}	δA_{zz}^{stat} $\times 10^{-2}$	δA_{zz}^{sys} $\times 10^{-2}$
0.30	0.24	0.99	1.84	—	—	—	0.18	2.13	1.84
0.40	0.28	0.26	1.84	—	—	—	0.12	1.38	1.84
0.50	0.32	0.21	1.84	0.14	3.52	1.84	0.11	1.23	1.84
0.60	0.19	0.41	????	0.12	2.26	????	0.18	0.78	????
0.70	0.13	0.68	????	0.18	1.33	????	0.28	0.48	????
0.80	0.19	0.48	0.48	0.30	0.72	0.48	0.42	0.31	0.48
0.90	0.39	0.22	1.10	0.46	0.45	1.10	0.54	0.24	1.10
1.00	0.52	0.16	????	0.52	0.43	????	0.58	0.25	????
1.10	0.39	0.28	1.27	0.43	0.63	1.07	0.53	0.33	0.95
1.20	0.22	0.65	2.54	0.30	1.15	2.14	0.40	0.55	1.91
1.30	0.14	1.34	3.81	0.19	2.16	3.22	0.32	0.83	2.87
1.40	0.09	2.29	5.06	0.14	3.52	4.29	0.24	1.31	3.82
1.50	0.06	4.09	6.35	0.10	5.85	5.37	0.20	1.86	4.78
1.60	0.04	7.76	7.60	0.06	10.4	6.45	0.14	2.87	5.74
1.70	0.04	9.23	8.88	0.05	13.5	7.52	0.10	4.53	6.69
1.80	0.03	14.9	9.20	0.06	13.9	8.60	0.11	4.73	7.66
2.00	0.67	3.79	9.20	0.20	3.05	9.20	0.70	0.45	9.20

Table 3: Summary of the expected uncertainty for each x bin for settings S2, S3, and H3.

Setting	Q^2 (GeV ²)	δT_{20}^{stat} $\times 10^{-2}$	δT_{20}^{sys} $\times 10^{-2}$
H2	1.8	13.2	4.7
S1	1.5	3.95	4.6
S2	0.7	5.36	4.6
H3	0.3	4.31	9.2
S3	0.2	0.64	5.5

Table 4: Expected uncertainties for T_{20} , assuming a systematic uncertainty of 9.2%, which could be reduced further by utilizing the S3 measurement as a calibration for the polarized target.

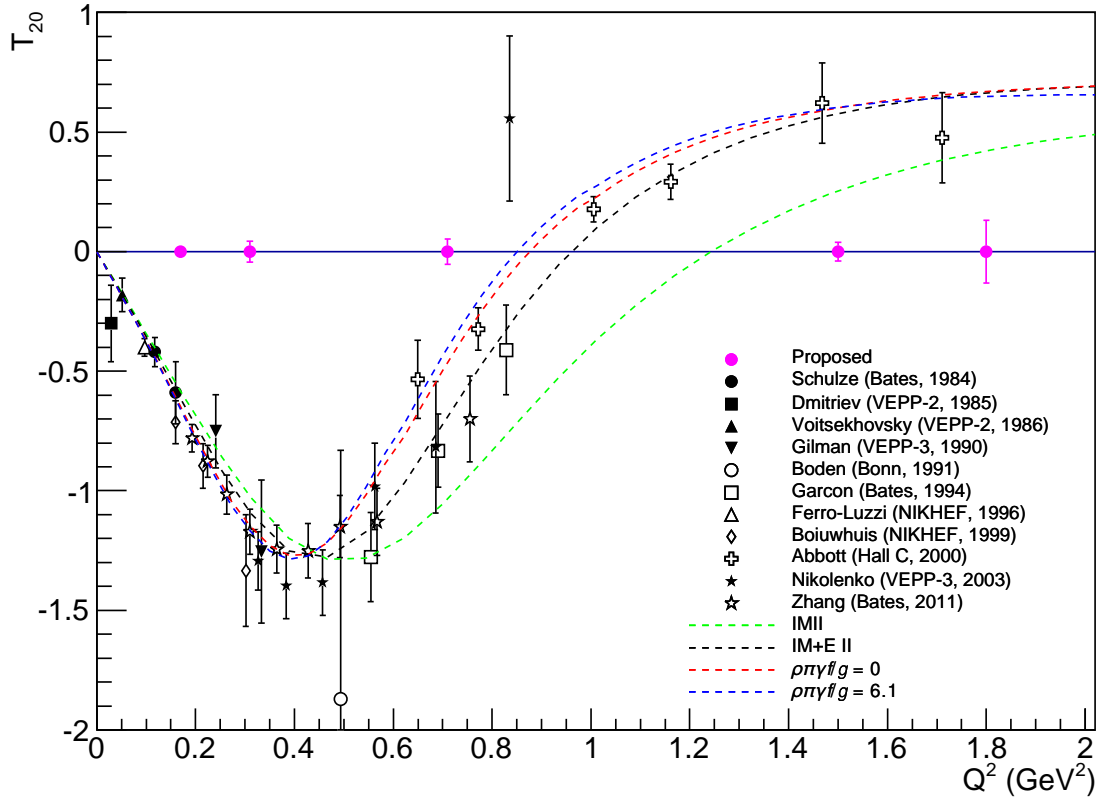


Figure 8: Projected statistical uncertainties for the elastic tensor analyzing power T_{20} with 34 days of beam time are shown alongside the world data [29].

3.4 Uncertainty Estimates

We discuss here the expected statistical and systematic uncertainties that we expect to contribute to the measurement.

3.4.1 Systematic Uncertainty

The spin-1 tensor-polarization dependent observables are part of the family of asymmetries which relies on obtaining data for two different target helicity states under equivalent experimental settings. A large contribution of the experimental uncertainty that effects absolute normalization cancels out as terms in the denominator and numerator are equivalent. For situations where the experimental configuration has changed during the data collection of the two different helicity states the cancellation does not occur and a rigorous accounting of the errors is required.

The tensor-polarization dependent asymmetry takes the form

$$A_{zz} = \frac{2}{fP_{zz}} \left(\frac{\sigma_p}{\sigma_u} - 1 \right), \quad (15)$$

where σ_p is the polarized cross section and σ_u is the unpolarized cross section. There are of course other spin-1 alignment dependent asymmetries, but for positive quadruple polarization in inclusive scattering all polarized observables can be expressed in terms of A_{zz} .

The figure of merit (FOM) for a tensor polarized solid state target can be defined as,

$$FOM = n_t f^2 P_{zz}^2 \quad (16)$$

where n_t is the target thickness and P_{zz} is the tensor polarization.

The contributions to the experimental uncertainty come from inaccuracies inherent in the system of measurement of the observable of interest. Each experiment contains instrumental components of systematic error which may or may not have dependence on accessible parameters. These types of errors can have a nonzero mean that changes over time so that its effect is not reduced when observations are averaged. There are also stochastic components to the uncertainty which will vary only around a single mean. There may still be a time dependence to the standard deviation of the stochastic contributions but these types of errors can be reliably estimated by repeating measurements.

Monitoring the systemic coupling of the instrumental parameters can greatly reduce the overall uncertainty produced in small asymmetry measurements. An understanding of the evolution of these types of errors over the course of the experiment can be used to make corrections after data acquisition. Reducing the time in each target spin orientation can also significantly reduce the impact of shifts in normalization. However, the stochastic components must be regulated prior to and during the experiment. Helicity flips can not reduce this type of uncertainty contribution.

Many of the errors that arise from limitations in measurement capacity have a statistical probability distribution that can be accurately estimated. For many of these types of uncertainties it is possible to derive confidence limits on the domain of the measured value resulting in a relative contribution to the total systematic error. Under an independent error assumption these relative contributions add in quadrature, with polarization being the dominating uncertainty in the spin

Source	Systematic
Polarization	6.0%
Dilution factor	6.0%
Packing fraction	3.0%
Trigger/Tracking Eff.	1.0%
Acceptance	0.5%
Charge Determination	1.0%
Detector resolution and efficiency	1.0%
Total	9.2%

Table 5: Estimates of the scale dependent contributions to the systematic error of A_{zz} .

dependent observables. The standard law of combination of errors does not work when there are correlations between these types of uncertainties. For this situation the full covariance matrix is required and a minimization procedure maybe needed to keep the error under control. This is only relevant for dominant errors. For multiple kinematic tracking variables strict estimation and handling of each uncertainty is essential for a complete analysis. In many cases one may wish to assume 100% correlation between variables to simplify the book keeping for smaller contributions.

Errors are often assumed to have a normal distribution. In reality measurement errors are rarely distributed in a true Gaussian and usually have some prominent non-Gaussian tail. Given a sufficient number of measurements the central limit theorem can be employed to ensure that the estimated parameters will be more Gaussian than the estimated measurements.

Table 5 shows a list of the scale dependent uncertainties contributing to the systematic error in A_{zz} .

Polarization error is well understood and steps will be taken to minimize these contributions, as has been done in previous experiments [30]. There are additional uncertainties that can arise from RF quadrupole polarization enhancement, but recent efforts by the UVA target group to study the tensor-enhanced NMR line-shape indicate that the total uncertainty in this case can be held under 6% [31, 32].

The dilution factor f varies as a function of scattered electron energy, particularly at kinematics where nucleon resonances are prominent. The dilution factor must be known precisely at each kinematic point. This factor must be based on empirical information with measurable error, which will be measured multiple times at each kinematic setting. Though the loss to the figure of merit can easily be recovered for lower f , the error calculated from the variation of the models is only a crude estimate.

The other uncertainties in Table 5 are very standard contributions which are difficult to reduce beyond the listed instrumental lower limit.

3.4.1.1 Time Dependent Factors

Eq. 15 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 sensi-

tivity to time dependent variations which will need to be carefully monitored and suppressed when possible. To investigate the systematic differences in the time dependent components of the integrated counts, the effects from calibration, efficiency, acceptance, and luminosity between the two polarization states must be considered. In order to look at the effect on A_{zz} due to drifts in beam current measurement calibration and detector efficiency, Eq. 15 is rewritten explicitly in terms of the raw measured counts N_1 and N ,

$$\begin{aligned} A_{zz} &= \frac{2}{fP_{zz}} \left(\frac{N_1^c}{N^c} - 1 \right) \\ &= \frac{2}{fP_{zz}} \left(\frac{Q\varepsilon l\mathcal{A}}{Q_1\varepsilon_1 l\mathcal{A}} \frac{N^1}{N} - 1 \right) \end{aligned} \quad (17)$$

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 $Q_1 = Q(1 - \delta Q)$. In this notation, δQ is a dimensionless ratio of charges in the different polarization states. A similar representation is used for drifts in detector efficiency leading to,

$$A_{zz} = \frac{2}{fP_{zz}} \left(\frac{N_1 Q (1 - \delta Q) \varepsilon (1 - \delta \varepsilon)}{N Q \varepsilon} - 1 \right). \quad (18)$$

which leads to,

$$A_{zz} = \frac{2}{fP_{zz}} \left(\frac{N_1}{N} (1 - \delta Q - \delta \varepsilon + \delta Q \delta \varepsilon) - 1 \right). \quad (19)$$

Estimates of δQ and $\delta \varepsilon$ can be obtained from previous experiments. For the HRS detector drift during the JLab transversity experiment E06-010, the detector response was measured such that the normalized yield for the same condition over a three month period indicated little change ($< 1\%$). These measurements indicated that for the short time (20 minutes) between target spin flips, the detector drift should be less than 1% times the ratio of the time period between target spin flips and three months. Also considering the period between target polarization states to be ≈ 12 hours leading to an overall drift $\delta \varepsilon \sim 0.01\%$. A similar approach can be used to establish an estimate for δQ using studies from the g2p/GEp experiment, resulting in $\delta Q \sim 0.01\%$. The SANE experiment with a beam current of 100 nA also provides some information. In this case, the relative stability of the current monitors is on the order of 1×10^{-3} , showing oscillations with a period of about an hour.

Expressing A_{zz} in terms of the estimated experimental drifts in efficiency and current measurement,

$$A_{zz} = \frac{2}{fP_{zz}} \left(\frac{N_1}{N} - 1 \right) \pm \frac{2}{fP_{zz}} \delta \xi. \quad (20)$$

where $\delta \xi = \delta Q + \delta \varepsilon$. This leads to a contribution to A_{zz} on the order of 1×10^{-3} ,

$$dA_{zz}^{drift} = \pm \frac{2}{fP_{zz}} \delta \xi = \pm 3.7 \times 10^{-3}. \quad (21)$$

Using the standard dilution factor and classically accessible polarization, the precision required in the raw A_{zz} measurement for already-approved DIS b_1 experiment is

$$\delta A_{zz}^{raw} = \frac{f P_{zz}}{2} \delta A_{zz} = 1.5 \times 10^{-4}. \quad (22)$$

For this proposed A_{zz} measurement, f is changing with x significantly. For $x \sim 1$ the dilution is greater ($f \sim 0.5$) than for the larger x ($f \sim 0.1$), where the large signal size indicated by A_{zz} model calculations requires considerably less precision. The critical point is $x \sim 0.8$ where f is less than 0.2 such that

$$\delta A_{zz}^{raw} = \frac{f P_{zz}}{2} \delta A_{zz} = \frac{(0.19)(0.2)}{2} (0.05) = 1.0 \times 10^{-3}. \quad (23)$$

So even this most sensitive point is still around an order of magnitude less constrained than the b_1 measurement.

Detector efficiencies can drift for a variety of reasons, including fluctuations in gas quality, high voltage drift, or drifts in the spectrometer magnetic fields. All of these types of variation can be controlled and minimized during the experiment through careful monitoring as well as systematic studies of the data collected. The identical configuration of the two polarization states minimizes the relative changes in luminosity with respect to time. Consistency checks on the measured cross section data can be implemented to ensure the quality of each run used in the asymmetry analysis. Fluctuations in luminosity due to target density variation can be kept to a minimum by keeping the material beads at the same temperature for both polarization states through control of the microwave and the liquid helium (LHe) evaporation. The helium vapor pressure reading provides an accuracy of material temperature changes at the level of $\sim 0.1\%$. Beam rastering can also be controlled to a high degree.

The dominant source of any variation in acceptance \mathcal{A} from state to state will be the stability of the target magnetic field. The capacity to set and hold the target super conducting magnet to a desired holding field is $\delta B/B = 0.01\%$. The same target cup will be used for each state, which removes any variation in the target length l .

3.4.1.2 Drift Mitigation

Uncertainty in the measuring devices (or resulting normalization deviations) must be small compared to the scale of the asymmetry at the helicity reversal frequency. The beam noise that can contribute to these normalization deviations comes from beam current, beam position, beam energy, beam size (consistent rastering), and beam halo. Detectors drifts in photomultiplier tube (PMT) gain can change the number of events above a discriminator threshold, which can become critical when the device PMT behavior changes significantly between helicity states. This is also true for drift chamber efficiency, spectrometer analyzing field, atmospheric pressure and temperature all affect these systems. The target holding field stability should never be an issue.

The most obvious way to improve the experiment considering these contributions is to increase the helicity flip frequency. Probably the most practiced way to do this is to use two different target cells alternating the cell position between a polarized target cell and an unpolarized target cell. By doing this additional uncertainties from using different packing fractions, effective target

densities, and target nuclear-chemical compositions are introduced that would not be present when using identical targets for each helicity state. These contributions may be able to be mitigated by alternating which cell is polarized. It is possible to polarize a particular cell without being in beam having it outside the homogeneous portion of the target field (beam line). In this way a target cell helicity can be prepared while taking data on the other cell. This could potentially allow multiple helicity changes in a 24 hour period.

In addition to greater frequency in helicity changes, the initial polarization build-up can also be enhanced. It is possible to install an electrically controlled microwave attenuator which will allow a larger amount of microwave power to dump into the target material to speed up polarization. The attenuator can then be adjusted to the required power to sustain polarization with the addition of the electron beam.

The uncertainty estimate in charge that results in a small absolute change in the observable is described in the proposal in the Section 3.4.1.1. Analytically there is a component of uncertainty that propagates with the other relative errors and only a very small piece that results in a drift in the observable. The resulting expression for the charge and other contributions to the drift in the observable is expressed as,

$$\delta A_{zz}^d = \pm \frac{2}{f P_{zz}} \delta \xi, \quad (24)$$

where $\delta \xi$ contains the sum of δQ , $\delta \epsilon$, δl , and δA . This means that to accurately represent δA_{zz}^d we must obtain only the residual deviation from the two polarization states in the time span of a single cycle (sampling of that data point). The value used for δQ is an estimate based on the actual effect seen in an observable which helps us to separate the relative contribution from the drift in a given time frame.

3.4.1.3 Trigger-Tracking For the most part, an easy way to determine whether or not drift will lead to an effect on the error is to determine if the change over time is seen in one polarization state and not the other with respect to the observable. Effects from trigger, cuts, and tracking efficiency do lead to errors in normalization, however both polarization states see the same stochastic fluctuation over the course of a cycle leading only to a small relative uncertainty in the observable. Aspects of the error that are non-stochastic and follow an unknown trend have been estimated in the proposal under the name ‘detector drifts.’ A secondary estimate was obtained based on HRS detector stability using Hall A transversity data for detected pions. The resulting drift was 2.2×10^{-4} . The detector thresholds will be set conservatively while using meticulous on-line monitoring and checks to the relative changes in tracking efficiency between slugs. For our present estimate including trigger, tracking, cuts, and detector errors that show up strictly as contributions to $\delta \xi$, we estimate no larger than 2.2×10^{-4} .

3.4.1.4 Target Dilution and Length There are presently UVA designs for target cup and material fabrication to minimize the probability of changes to target dilution in the form of material loss over time. The cup contains multiple hole arrays that are only a 0.1 mm in size. The material shape and consistency is optimized to maximize the packing fraction and minimize the fracturing capacity. The ammonia is hand selected to reduce the structural faults to obtain beads approximately

2 mm in diameter which have already undergone multiple steps of mechanical stress including being pre-irradiated at NIST with a $10\ \mu\text{A}$ beam. The temperature and thus the density of the target is kept the same in both polarized and unpolarized states. There are four temperature sensors in a standard solid polarized target setup that can be used to monitor this. The temperature is controlled via LHe evaporation, microwave, and beam heating. All three are used to maintain consistent temperature in both polarization states.

The polarized material to be used in the experiment will be contained in 3 cm long, 2.54 cm diameter cylinder cups with their axes parallel to the beam. The cylinders fit inside the 4 cm diameter vertical cylindrical tail piece at the bottom of the refrigerator. The tail piece is full of liquid helium to about 20 cm above the beam level. The heat and radiation of the beam is distributed uniformly over the cross section of the target normal to the incident beam by a combination of slow and fast rasters. The fast raster normally is a 2mm by 2mm square shape, traced by the sub-millimeter beam at kHz rates. The slow raster normally is a 1 cm maximum radius spiral, traced at constant tangential speed, covering the rastered area with 5% dose uniformity at 30 Hz and can be synchronized to the usual helicity flip signals [33].

The averaging of the target length done by the rasters results in an effective length that is determined by the fraction of the cup volume (equivalently, the rastered volume) that is filled with ammonia [33]. A possible change in the effective target length between the polarized and unpolarized periods of a measurement cycle could come from a net change of material in the raster volume. Since the raster diameter is 25% smaller than the cup diameter, there is always material outside the raster region that would fill in an unlikely loss in the rastered region. A possible estimate of the length change can be obtained by considering the ratio of the $0.008\ \text{cm}^3$ volume of a fragment to the $6.8\ \text{cm}^3$ raster volume (including packing fraction) the ratio is $\sim 1/850$.

The only documented instance with ammonia polarized targets and CEBAF $\sim 100\ \text{nA}$ beams of a possible rearrangement of material about the target NMR coil that might indicate an associated net change in material was seen during E07-003 (SANE) which took about 500 hours of $\geq 85\ \text{nA}$ beam. During one 20 h polarized and unpolarized cycle, the loss of 1 or 2 fragments would result in a $\sim 1 \times 10^{-3}$ change in target length, with a $\sim 20\text{h}/500\text{h}$ probability. No instances of material fragmentation, which could potentially lead to net losses in the raster region have been observed with up to 150 nA CW CEBAF beams (E93-026, E01-006, E07-003). In addition, there are checks in NMR data that can be used to ensure that no loss of a target fragments occurred between cycles.

The only instances of material fragmentation for ammonia targets were observed at SLAC, in the E143/E155/E155x series of experiments, but the SLAC beam is pulsed, with $4\ \mu\text{s}$ wide pulses of $\sim 20\ \mu\text{A}$ current at 120 Hz repetition rate. Such beam time structure can be expected to damage the ammonia crystals by thermal shock. In fact, to further prevent possible shock effects at JLab, the polarized target experiments in Hall C implemented the procedure of gradual ramping up of the beam current after beam trips.

All changes to the material that occur during movement of the target ladder or annealing can only happen at the end of each pair of measurement cycles and are irrelevant for the preceding or following cycles. Small changes to material NMR loop coupling are consistent to both polarization states and exist as a relative error in the polarization. In addition, as long as the LHe is superfluid ($< 2\ \text{K}$), its flow can not lead to material rearrangements. The LHe that is fed at the bottom of the

nose piece coming from the separator is below 2 K, so emptying and refilling does not have any effect.

Depolarization using LHe is a relatively standard technique. In this procedure, the beam is turned off and the LHe fill valve that controls the LHe level that surrounds the target insert is slowly reduced as to not replenish the LHe evaporation until the material has warmed up and the polarization has died out. The LHe is gradually filled again as in the standard evaporation mode and again set on automated control. Once the material is unpolarized and again submerged under the LHe the microwaves are turned on in off-resonance mode. The unpolarized target is then ready for beam. This procedure provides a quick way to kill polarization while returning the unpolarized state to the exact condition of the polarized state. The small fluctuation in density, temperature and NMR material couple occur in both states and are a small relative error in the polarization. All other aspects that may result in addition to the drift are negligible.

For example, the target operating temperature is $\sim 1.1 \pm 0.15$ K, well below the superfluid point. Over that range, the LHe density, changes by 4×10^{-5} (the density actually increases below $\simeq 1.1$ K and increases above, by about equal amounts over the temperature interval [34]). The lattice constant of deuterioammonia [35] changes from 5.048 Å at 2 K to 5.073 Å at 77 K, corresponding to a 1×10^{-5} change over the ± 0.15 K interval considered above. For a 60% packing fraction, the change would be 2.3×10^{-5} for a 0.15 K unexpected temperature difference between polarization states. Any possible unaccounted changes in target length between the polarized and unpolarized parts of each cycle can also be monitored by recording the time dependence of the luminosity with a $\simeq 0.5 \times 10^{-4}$ accuracy.

3.4.1.5 Solid Angle

The error that arises in the observable due to beam position and magnet currents over time is inherently very difficult to separate into drift and relative uncertainty. The 0.1% error over a 12 hour period is probably quite accurate, however, being that both polarization states experience the same fluctuations its likely that the majority of the uncertainty is relative. There are also concerns on acceptance due to beam position drift. Beam drift will be monitored during the experiment and accounted for during analysis. The largest part of this uncertainty is also a relative contribution to both target states. The contribution to the drift can be minimized with the feedback system built for parity experiments .

Trends that arise from dependence of yield on magnet currents in detectors are a concern related to the spectrometer acceptance. The drift effect can be made to be small, for the HRS typically less than 10^{-4} for the dipole and 10^{-3} for the three quads, and similarly for the HMS. The effects on the acceptance can be determined and corrected through careful analysis. Naturally, the target magnet current does not need to be changed between cycles, as the uniformity, stability, and setability pointed out in the proposal eliminate field variation between the two polarization states. The residual drift from solid angle effects after such correction is expected to be no larger than 0.01%. This value was already accounted for in Section 3.4.1.3.

3.4.1.6 Beam Current Monitors

Information has been extracted from experiment E06-010 for high current (10-15 μ A), in which

all the systematics are included in the yield studies including detector drift, acceptance drift, BCM drift and acceptance due to BPM drift. The beam charge asymmetries between two helicity states using the luminosity monitors for experiment E06-010 has been shown to be at the level of 4×10^{-5} with a width of 2.3×10^{-4} . An additional estimate on the change in the BCM calibration constant is seen in experiment E08-027 resulting in a absolute deviation of 2.0×10^{-4} over the course of six days. Long term drifts can be reduced by careful thermal isolation of the BCMs, however resulting trends will be need to be studied and corrections implemented.

Fluctuations in the calibration of beam current measuring devices can be well understood and mitigated. Even when calibrations are taken frequently, a small change in the BCM response over the course of a single helicity flip iteration can contribute a drift on the order of 1×10^{-4} . A Boosted Decision Tree regression maybe used similar to that used for the temperature dependence of the Q-meter. This would require accurate temperature monitoring of the BCM stainless steel pillbox resonant cavity in operation. Creating a heat regulating system using a fluid circulated chiller could help to both stabilize and accurately measure the temperature. Additional temperature stabilization of analog cables, and optimizing cable length maybe also help.

3.4.1.7 Systematic Summary

It is essential to consider each uncertainty and each source separately as well as understand systemic coupling. This proposed A_{zz} measurement would be a great benefit to understand and minimize systematic uncertainties for small asymmetry measurements such as b_1 . Having data at a large range of beam current, energy, and target types while studying beam noise and detector stability can help to build a comprehensive map of critical systematic issues. Other systematic minimization techniques can be explored during A_{zz} in addition to the systematic minimization mentioned in this proposal, which will be critical for b_1 [citation needed] and could help many other future experiments. In fact there is no better experimental opportunity to study the systematics of probing asymmetries in Hall C then A_{zz} at high x . Because of the scale of the predicted asymmetry A_{zz} for large x , the drifts that can corrupt b_1 are only relevant for the lower x points, although for A_{zz} in this region a systematic error of the order of (1×10^{-3}) would be very good, which has an order of magnitude more leeway then for b_1 .

3.4.2 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),

$$A_{zz} = \frac{2}{fP_{zz}} \left(\frac{N_p}{N_u} - 1 \right). \quad (25)$$

The statistical error with respect to counts is then

$$\delta A_{zz} = \frac{2}{fP_{zz}} \sqrt{\left(\frac{\delta N_p}{N_u} \right)^2 + \left(\frac{N_p \delta N_u}{N_u^2} \right)^2}. \quad (26)$$

590 For $\delta N_{p(u)} = \sqrt{N_{p(u)}}$, the uncertainty becomes

$$\delta A_{zz} = \frac{2}{fP_{zz}} \sqrt{\frac{N_p(N_u + N_p)}{N_u^3}}, \quad (27)$$

591 which can't be simplified further due to the large expected asymmetry.

592 The number of counts was calculated using a combination of P. Bosted's [27] and M. Sargsian's [20]
 593 code for $x < 2$. The Bosted code was used for the lowest Q^2 setting, where effects of SRC scaling
 594 are expected to be negligible, and for $x < 1.1$ to accurately determine the quasi-elastic peak. The
 595 Sargsian code was used for the higher Q^2 settings at $x > 1.1$ due to its inclusion of SRC scaling
 596 effects.

597 The deuteron elastic peak was calculated using a parametrization of the deuteron elastic form
 598 factors A and B by

$$\frac{d^2\sigma}{d\Omega dE'} = \sigma_{\text{Mott}} \left(\frac{E'}{E} \right) \left[A + B \tan^2 \left(\frac{\theta}{2} \right) \right] \delta(E' - E'_{el}), \quad (28)$$

599 where $\delta(E' - E'_{el})$ is approximated by a Gaussian distribution with its width determined by the
 600 resolution of the spectrometers,

$$\delta(E' - E'_{el}) = \frac{1}{2\Delta E \cdot E'_{el} \sqrt{\pi}} e^{-\frac{(E' - E'_{el})^2}{2(\Delta E \cdot E'_{el})^2}}, \quad (29)$$

601 where $\Delta E = 0.1$ (0.08)% for the HMS (SHMS) and $E'_{el} = \frac{Q^2}{2m_D}$. This was added to the rates
 602 calculation that was used for quasi-elastic A_{zz} and b_1 [36], and the uncertainty of A_{zz} on the elastic
 603 peak was calculated the as in Eq. 27.

604 Following the methodology discussed in Section 3.2, to obtain statistical uncertainties for T_{20}
 605 we scale our calculated elastic A_{zz} uncertainties by

$$\delta t_{20} = \sqrt{2} \delta A_{zz}. \quad (30)$$

606 The projected uncertainties for A_{zz} are summarized in Tables 2-3 and displayed in Figs. 6-7.
 607 The projected uncertainties for T_{20} are summarized in Table 4 and displayed in Fig. 8.

608 3.5 Polarized Target

609 This experiment will use the JLab/UVa dynamically polarized solid ND₃ target operated in longi-
 610 tudinal mode. The target is typically operated with a specialized slow raster and beamline instru-
 611 mentation capable of characterizing the low current 50-100 nA beam. All of these requirements
 612 have been met previously in Hall C. The polarized target (see Fig. 9), has been successfully used in
 613 experiments E143, E155, and E155x at SLAC, and E93-026, E01-006 and E07-003, E08-027 and
 614 E08-007 at JLab. A similar target was used in Hall B for the EG1, EG4, and DVCS experiments.

615 The JLab/UVa target underwent significant renovation and improvement [37] during the recent
 616 g2p run. The magnet was replaced early in the run, and the target then performed consistently. A

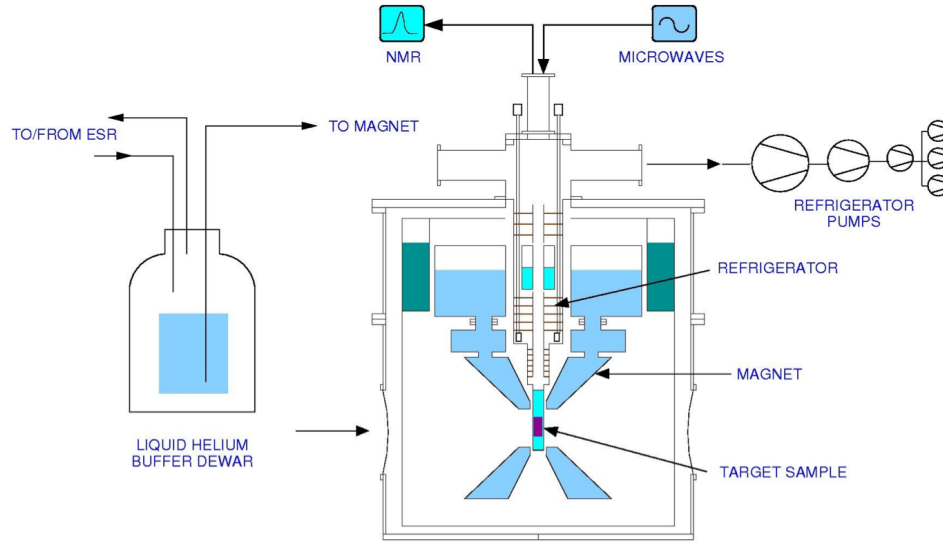


Figure 9: Cross section view of the JLab/UVa polarized target. The proposed experiment will use the modified Hall B magnet, where the backwards-scattering cone is blocked with quench protection circuitry. Figure courtesy of C. Keith.

new 1 K refrigerator and target insert were designed and constructed by the JLab target group. The cryogenic pumping system has been overhauled. In particular, the older Alcatel 2060H rotary vane pumps have been replaced with new Pfeiffer DU065 magnetically coupled rotary vane pumps, and the pump controls are being refurbished. The target motion system has been rebuilt from scratch.

The target operates on the principle of Dynamic Nuclear Polarization, to enhance the low temperature (1 K), high magnetic field (5 T) polarization of solid materials by microwave pumping. The polarized target assembly contains several target cells of 3.0 cm length that can be selected individually by remote control to be located in the uniform field region of a superconducting Helmholtz pair. The permeable target cells are immersed in a vessel filled with liquid Helium and maintained at 1 K by use of a high power evaporation refrigerator. The coils have a 50° conical shaped aperture along the beam axis which allow for unobstructed forward scattering.

The target material is exposed to microwaves to drive the hyperfine transition which aligns the nucleon spins. The heating of the target by the beam causes a drop of a few percent in the polarization, and the polarization slowly decreases with time due to radiation damage. Most of the radiation damage can be repaired by periodically annealing the target, until the accumulated dose reached is greater than about $0.5 \times 10^{17} \text{ e}^-/\text{cm}^2$, at which time the target material needs to be replaced.

3.5.1 Polarization Analysis

The three Zeeman sublevels of the deuteron system ($m = -1, 0, 1$) are shifted unevenly due to the quadrupole interaction [38]. This shift depends on the angle between the magnetic field and

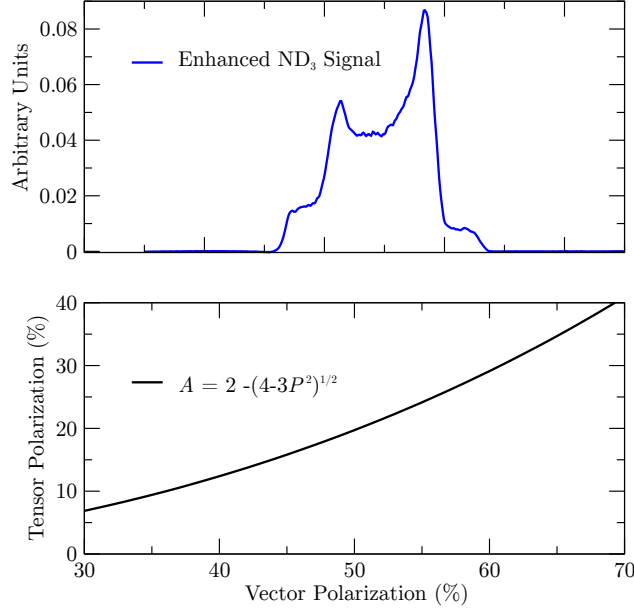


Figure 10: **Top:** NMR signal for ND₃ with a vector polarization of approximately 50% from the GEN experiment. **Bottom:** Relationship between vector and tensor polarization in equilibrium, and neglecting the small quadrupole interaction.

the electrical field gradient, and gives rise to two separate transition energies. Hence, the unique double peaked response displayed in Fig. 10. When the system is at thermal equilibrium with the solid lattice, the deuteron polarization is known from:

$$P_z = \frac{4 + \tanh \frac{\mu B}{2kT}}{3 + \tanh^2 \frac{\mu B}{2kT}} \quad (31)$$

where μ is the magnetic moment, and k is Boltzmann's constant. The vector polarization can be determined by comparing the enhanced signal with that of the TE signal (which has known polarization). This polarimetry method is typically reliable to about 3.9% relative.

Similarly, the tensor polarization is given by:

$$P_{zz} = \frac{4 + \tanh^2 \frac{\mu B}{2kT}}{3 + \tanh^2 \frac{\mu B}{2kT}} \quad (32)$$

From Eqs. 31 and 32, we find:

$$P_{zz} = 2 - \sqrt{4 - 3P_z^2}$$

In addition to the TE method, polarizations can be determined by analyzing NMR lineshapes as described in [39] with a typical 7% relative uncertainty. At high polarizations, the intensities of the two transitions differ, and the NMR signal shows an asymmetry in the value of the two

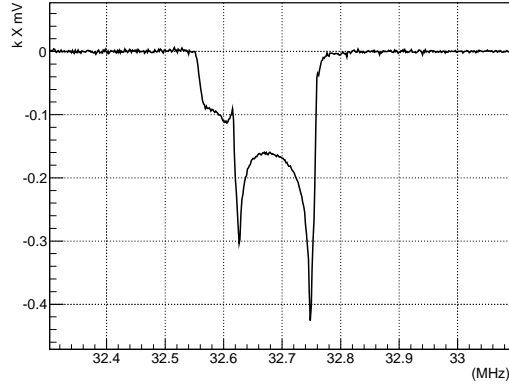


Figure 11: The deuterium magnetic resonance line shape showing the recent achievement of high tensor polarization of deuterated butanol after RF saturation of a pedestal at the UVA polarized target lab accomplished during their April 2014 cool-down.

peaks, as shown in Fig. 10. The vector polarization is then given by:

$$P_z = \frac{R^2 - 1}{R^2 + R + 1} \quad (33)$$

and the tensor polarization is given by:

$$P_{zz} = \frac{R^2 - 2R + 1}{R^2 + R + 1} \quad (34)$$

This measuring technique can be used as a compliment to the TE method resulting in reduced uncertainty in polarization.

3.5.2 Tensor Polarization Enhancement

It is possible to enhance tensor polarization using RF irradiation on the oriented deuterium nuclei to manipulate the alignment. Applying a saturating RF field on the pedestal of the smaller transition equalizes the substate $m = +1$ and $m = 0$ populations over 2/3 of the NMR signal. This equalization over the range of a single pedestal leads to enhancement in tensor polarization with only a small loss to the overall area ($\sim 2\%$). Very recent studies at UVA using deuterated butanol have indicated that the tensor polarization can be increased by using a modified hole burning technique. The result will be investigated in the near future, and the method applied to ND_3 . The studies also indicate that microwaves used during DNP does not interfere with the saturation from the RF irradiation when sufficient power is used. This implies that RF over the pedestal can be done the same time DNP is performed to enhance the area while taking beam in an experiment. Research and development is ongoing to study various techniques to optimize tensor enhancement for nuclear experiments targets.

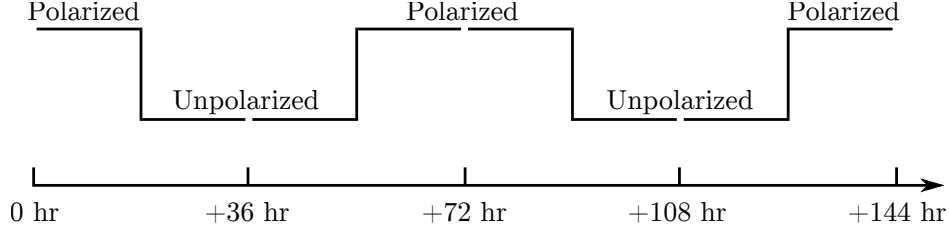


Figure 12: A visual demonstration of how the polarization cycle will happen over a 72 hour period to reduce time-dependent systematic effects. For the two lower Q^2 measurements, the cycle will happen over a 18 hour period.

3.5.3 Depolarizing the Target

To move from polarized to unpolarized measurements, the target polarization will be annihilated using destructive NMR loop field changes and destructive DNP microwave pumping. During unpolarized data taking the incident electron beam heating is enough to remove the thermal equilibrium polarization.

We are able to verify that the target is in the unpolarized state via NMR measurements. The target material will be kept at 1 K for polarized and unpolarized data collection, and the target field will be held constant for both states as well. These consistencies are used to minimize the systematic differences in the polarized and unpolarized data collection. To minimize systematic effects over time, the polarization condition will be switched twice in a 72 hour period, as shown in Fig. 12. This will be sufficient to account for drift in integrated charge accumulation.

3.5.4 Dilution Factor

To derive the dilution factor, we first start with the ratio of polarized to unpolarized counts. In each case, the number of counts that are actually measured, neglecting the small contributions of the thin aluminium cup window materials, NMR coils, etc., are

$$N_1 = Q_1 \varepsilon_1 \mathcal{A}_1 l_1 [(\sigma_N + 3\sigma_1)p_f + \sigma_{He}(1 - p_f)], \quad (35)$$

and

$$N = Q \varepsilon \mathcal{A} l [(\sigma_N + 3\sigma)p_f + \sigma_{He}(1 - p_f)]. \quad (36)$$

where Q represents accumulated charge, ε is the detector efficiency, \mathcal{A} the cup acceptance, and l the cup length.

For this calculation we assume similar charge accumulation such that $Q \simeq Q_1$, and that the efficiencies stay constant, in which case all factors drop out of the ratio leading to

$$\begin{aligned} \frac{N_1}{N} &= \frac{(\sigma_N + 3\sigma_1)p_f + \sigma_{He}(1 - p_f)}{(\sigma_N + 3\sigma)p_f + \sigma_{He}(1 - p_f)} \\ &= \frac{(\sigma_N + 3\sigma(1 + A_{zz}P_{zz}/2))p_f + \sigma_{He}(1 - p_f)}{(\sigma_N + 3\sigma)p_f + \sigma_{He}(1 - p_f)} \end{aligned}$$

Overhead	Number	Time Per (hr)	(hr)
Polarization/depolarization	38	2.0	76.0
Target anneal	15	4.0	60.0
Target T.E. measurement	6	4.0	24.0
Target material change	4	4.0	16.0
Packing Fraction/Dilution runs	20	1.0	20.0
BCM calibration	9	2.0	18.0
Optics	3	4.0	12.0
Linac change	2	8.0	16.0
Momentum/angle change	3	2.0	6.0
			10.3 days

Table 6: Major contributions to the overhead.

$$\begin{aligned}
&= \frac{[(\sigma_N + 3\sigma)p_f + \sigma_{He}(1 - p_f)] + 3\sigma A_{zz}P_{zz}/2}{(\sigma_N + 3\sigma)p_f + \sigma_{He}(1 - p_f)} \\
&= 1 + \frac{3\sigma A_{zz}P_{zz}/2}{(\sigma_N + 3\sigma)p_f + \sigma_{He}(1 - p_f)} \\
&= 1 + \frac{1}{2}f A_{zz}P_{zz}, \tag{37}
\end{aligned}$$

where $\sigma_1 = \sigma(1 + A_{zz}P_{zz}/2)$ has been substituted, per Eq. 3, with $P_B = 0$. It can be seen that the above result corresponds to Eq. 6.

3.6 Overhead

Table 6 summarizes the expected overhead, which sums to 10.3 days. The dominant overhead comes from switching from the polarized to unpolarized state and vice versa, and target anneals. The target will need to be annealed about every other day, and the material replaced once a week. Measurements of the dilution from the unpolarized materials contained in the target, and of the packing fraction due to the granular composition of the target material will be performed with a carbon target.

4 PAC42 Comments and Concerns

In this section we summarize the comments and concerns that were raised by the PAC42 committees on letter of intent LOI12-14-002.

4.1 Theory Advisory Committee

“This Letter of Intent describes a measurement of the tensor-polarized asymmetry A_{zz} in electron scattering on polarized deuterium in the quasi-elastic region, at val-

ues of $x = 0.8 - 1.75$ (x is the equivalent Bjorken variable at the nucleon level) and $Q^2 = 12 \text{ GeV}^2$. The aim is to determine with this observable the S/D wave ratio in the deuteron wave function at large relative momenta $k > 300 \text{ MeV}$, which is important for understanding the NN interaction at short distances and the properties of the dominant pn short-range correlations in heavier nuclei. The same tensor-polarized asymmetry was/will be measured in elastic scattering (deuteron form factor) and deep-inelastic scattering (structure function b_1); the proposed measurement in quasi-elastic scattering would fill the gap and study this observable in the region where it is most directly related to the short-range NN interaction. The tensor asymmetry at large recoil momenta also serves as a sensitive test of “relativistic effects” in the treatment of deuteron structure, which are an important aspect of the overall theoretical framework and the object of ongoing studies. A unique feature of the measurement proposed here is that it selects small-size configurations in the deuteron both through the tensor asymmetry (D -state) and the choice of kinematics ($x > 1$), amplifying the overall effect. The use of $x > 1$ for selecting small-size NN configurations has been demonstrated in previous studies of deep-inelastic structure.

The measurement proposed here arises from a well-developed context, presents a clear objective, and enjoys strong theory support. It would further explore the nature of short-range pn correlations in nuclei, the discovery of which has been one of the most important results of the JLab 6 GeV nuclear program. Development of a full proposal should be encouraged.”

4.2 Technical Advisory Committee

“This experiment utilizes the same apparatus and techniques as the conditionally approved b1 experiment C13-12-011. The comments in the TAC report for that experiment also apply to this experiment.

The requirement to understand and mitigate time-dependent systematic effects may be less as the asymmetry A_{zz} , at least for $x > 1$, is expected to be larger than for b1. However, measuring with $\delta A_{zz} < 0.10$ still requires a systematic control of the raw asymmetry to better than 1%. This is still challenging with a target polarization that is cycled on and off about once a day. Furthermore, at $x > 1$, short range structure enhances inclusive cross sections in nuclei relative to deuterium. This will reduce the dilution factor for $x > 1$ measurements, reducing the raw asymmetries to levels where understanding and controlling systematic errors will still be important.”

4.3 Program Advisory Committee

“Measurement and Feasibility: Electron scattering off tensor-polarized deuterium would be measured in the quasi-elastic region using the Hall C HMS and SHMS spectrometers. This proposal would use the same setup as the C1-approved experiment

E12-13-011, which is to measure the deuteron tensor structure function b_1 . The C1-approval is subject to demonstration that 35% tensor polarization is possible. The expected asymmetry is larger in the case of this measurement, but we anticipate that a similar requirement would apply. It is anticipated that a full proposal would be for 39 days, which would include 30 days for three different Q^2 values and 9.1 additional days of overhead.

Issues: A significant amount of beam time will be required for this measurement. A full proposal will need a detail discussion of expected systematic and statistical errors similar to what is in the letter that carefully justifies the requested time. The proposal should also demonstrate what sensitivity they will have to NN interaction models, such as the 6-quark model, final state interaction models, and NN interaction models, mentioned in the proposal. It will also be important to discuss how the results will distinguish between effects from the NN-interaction, the treatment of these interactions at high virtuality, and the intrinsic deuteron wave function.

Recommendation: Proceed to proposal addressing the issues noted above.”

4.4 Response to PAC42 Concerns

The tensor polarization of 30% used in the rates for this proposal is the same as condition on the E12-13-011 proposal, which was incorrectly mentioned as 35%. To ensure that the target is not significantly affected by the electron beam, we’ve estimated a current of 90 nA, as opposed to the 115 nA beam for b_1 . We have expanded upon our estimated statistical and systematic uncertainties in Section 3.4 and in a recent technical note [\[citation needed\]](#), where we stress that a measurement of A_{zz} in the $x > 1$ region is ideal for understanding time-dependent systematic effects without significantly affecting the measurement. Furthermore, we will be measuring T_{20} at low Q^2 where it is well understood both experimentally and theoretically, which can be used as a calibration to reduce our leading systematics from understanding the target polarization. However, for the uncertainty calculations in this proposal we retain a conservative estimate of 12%.

Since PAC42, we have engaged a number of theorists who have provided models not only between light cone and virtual nucleon models, but also using different NN interaction potentials [19] and final state interactions [\[citation needed\]](#). Furthermore, A_{zz} calculations are being performed at low Q^2 and are expected to be completed within a year [\[citation needed\]](#). Although our measurements will be at too low W^2 to probe 6-quark, hidden color effects through an extraction of b_1 , they are ideal for making a simultaneous measurement of T_{20} to test existing calculations at large Q^2 , as discussed in Section 3.2, including in the region where recent Hall A and Hall C data show a discrepancy.

5 Summary

We have investigated the possibility of making high precision measurements of the quasi-elastic tensor asymmetry A_{zz} . By covering the kinematic range from the QE peak ($x = 1$) up to elastic

scattering ($x = 2$), we expect that this data will provide valuable new insights about the high momentum components of the deuteron wavefunction. We are actively working with several theorists to get state-of-the-art calculations of light cone, virtual nucleon, and six-quark models. Additional calculations are being performed that include final-state interactions, and low Q^2 sensitivity to NN potentials. It is important to note that this is the same kinematic region that has been shown to be correlated with the EMC effect via the $x > 1$ A/D (e, e') results.

We have found that with 34 days of beam and an additional 10.3 days of overhead, A_{zz} can be measured with high precision at $Q^2 = 1.5, 0.7$, and $0.3 \text{ (GeV}/c)^2$ in Hall C using identical equipment as the upcoming b_1 measurement while being less sensitive to systematic uncertainties. In addition, it will fill a gap in measurements of A_{zz} between the $T_{20} \propto A_{zz}$ elastic measurements and the $b_1 \propto \frac{A_{zz}}{F_1^d}$ deep-inelastic measurements.

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