Measurement of the Gerasimov-Drell-Hearn Integral at low Q^2 on the Deuteron and Neutron

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Abstract

We propose to measure the Gerasimov-Drell-Hearn (GDH) integral for the deuteron at low momentum transfer ($0.015 < Q^2 < 0.2$ GeV^2). This will provide a check of Chiral Perturbation theory and Lattice calculations without the issue of nuclear corrections, and presents a significant test of our understanding of the properties of few-body nuclei. By combining these data with the proton data taken under similar conditions in E03-006 [1], we will extract the GDH integral on the neutron. The combined data sets will provide a self-consistent test of the Bjorken sum, an excellent quantity to measure in the context of linking the partonic and hadronic descriptions of the strong interaction. The choice of kinematics will also allow extrapolation to $Q^2 = 0$, in order to check the (real photon) GDH sum rule for both the deuteron and neutron. Due to the complexity of nuclear medium effects at low momentum transfer, neutron extraction from multiple nuclei is essential. As such, our proposal will complement experiment E97110 [2], which utilized a ^{3}He target, and will be vital to constrain the uncertainty from nuclear extraction.

The experimental conditions of this proposal are identical to E03-006, aside from the target cell, and all requested beam energies are less than 2.0 GeV, which matches the constraints of the near-term beam schedule. To perform this measurement, we request 20 days of beam time.

Contents

Preface

This document is an update of proposal 05-111 which was presented at PAC 28. The PAC report is reproduced here, and the PAC's comments are addressed. In addition, there are several other major changes in the main body of this document from the 05-111 proposal:

- There is more discussion on the measurement of the deuteron GDH sum. In particular, we examine the sub-threshold contribution in Section 2.1 and Appendix A.
- The neutron extraction uncertainty arising from nuclear corrections in the deuteron and ^{3}He are discussed in greater detail in Sections 2.3 and 4.1.
- Scheduling considerations and the benefits of running this experiment immediately after E03-006 are discussed in this preface.

PAC 28 comments

The PAC 28 report on PR 05-111 is reproduced below:

Proposal: PR 05-111

Scientific Rating: N/A

Title: Measurement of the Gerasimov-Drell-Hearn Integral at low Q^2 on the Neutron and Deuteron

Spokespersons: Alexandre Deur, Gail Dodge and Karl Slifer

Motivation: The proposal aims at measuring the generalized ($Q^2 \neq 0$) GDH integral for the deuteron at Q^2 down to 0.01 (GeV/c)^2 in a Hall B experiment using the CLAS detector and a polarized deuterium target (ND$_3$). By combining the results with the approved experiment on the proton target (NH$_3$) in Hall B (E03-006), this proposal should allow the determination of this integral and therefore a test of the GDH sum rule on the neutron at Q^2 close to 0. This will complement data of a similar but less accurate experiment (EG1b) already performed in Hall B at Q^2 above 0.05 (GeV/c)^2.

Measurement and Feasibility: The experiment is proposed in Hall B for 30 days. The experimental set-up uses the CLAS detector with a new Cerenkov counter for absolute normalization. The polarization of electrons is assumed to be 80% and a beam current of 1-4 nA is required. This proposal relies on the operation of a polarized solid target (ND3) with 40% deuteron polarization. The experimental specifications appear to be reachable with CLAS, which will be used in rather standard operation. The new Cerenkov counter is under construction for E03-006 and will be available. The determination of the sum rule for the deuteron will include the disintegration channel which is large below pion threshold where the elastic channel also contributes. The extraction of the neutron GDH integral relies on nuclear corrections which are not small in the case of a deuteron target. It will make use of the combination of data from this proposal and from the proton data (E03-006) which will cover about the same kinematics.

Issues: The beam and target polarizations used in the proposal might be too high and safer values of 75% and 30% have been assumed respectively. The PAC recognized the great importance of the measurement of the GDH sum rule for the neutron at very low Q^2 which will also allow an extrapolation to the photon point. However, an experiment (E97-110) has already collected data in Hall A with a polarized ^{3}He target which provides a cleaner source of polarized neutrons. The present proposal offers no large improvement in accuracy and only a moderate extension toward lower Q^2 with respect to the projected E97-110 results. Therefore it will be important to wait for the results of E97-110 for a better judgment of the need for an additional measurement with a nuclear target (ND_3 instead of ^{3}He).

Recommendation: Defer

Response

We first note that there was no question regarding the high physics motivation of the proposal, as '*the PAC recognized the great importance of the measurement of the GDH sum rule for the neutron at very low Q^2, which will also allow an extrapolation to the photon point*'. This is consistent with previous ratings from the PAC on GDH physics.

We also note that the PAC raised no concern over the experiment's feasibility, observing that '*the experimental specifications appear to be reachable in CLAS, which will be used in rather standard operation.*'

In the following sections, we address the issues raised by the PAC.

^{3}He as a cleaner source of polarized neutrons

PAC 28 issue: *an experiment (E97-110) has already collected data in Hall A with a polarized ^{3}He target which provides a cleaner source of polarized neutrons.*

It is true that ^{3}He possesses some advantages compared to the deuteron, when it comes to neutron extraction. For example, the proton correction comes at second order, since the proton spins tend to anti-align due to the Pauli principle. On the other hand, ^{3}He is a more complex and more tightly bound nucleus. As a consequence, the method used for nuclear correction is more uncertain [3, 4] for ^{3}He. At the low Q^2 of this proposal, the advantage of the small relative size of the proton correction in ^{3}He does not necessarily outweigh the increased uncertainty in the technique of nuclear extraction from ^{3}He. The total extraction uncertainty is, in fact, similar for the two nuclei. We discuss this in detail in Section 4.1, where we deomonstrate the complementarity of ^{3}He vs. deuteron as neutron sources. This is especially valuable for this proposal since one of its main goals is to bring confidence in neutron results by providing neutron quantities with different nuclear systematic uncertainty.

The belief that a ^{3}He target provides a better source of neutron may come from the fact that, in general, neutron results from ^{3}He are more statistically precise than their deuteron counterparts. This is due to the significantly better figure of merit of a polarized ^{3}He target (higher polarization, higher beam current, less dilution). However, this is of less importance at low Q^2 were counting rates are high, and where the nuclear corrections for ^{3}He and deuteron are of the same level. Also, CLAS partially compensates for the lower figure of merit with its large acceptance. We stress that the the quality of the data on D from this proposal and from the ^{3}He E97-110 experiment are expected to be comparable for the lowest Q^2 points. This is illustrated in Figure 7.

The merit of deuteron vs ^{3}He at low Q^2 was only briefly described in our PAC 28 presentation. We discuss this point more thoroughly in Section 4.1.

Accuracy compared to E97-110

PAC 28 issue: *The present proposal offers no large improvement in accuracy and only a moderate extension toward lower Q^2 with respect to the projected E97-110 results. Therefore it will be important to wait for the results of E97-110 for a better judgment of the need for an additional measurement with a nuclear target (ND_3 instead of ^{3}He).*

As stated on page 8 of PR-05-111, " It is not the goal of this proposal to improve on the measurement done in Hall A. However, we can reach a comparable precision below $Q \approx 0.1$ GeV^2 where the neutron extraction method starts to be unreliable and where a cross check is most valuable." A high precision result from experiment E97-110 is actually required to achieve one of the goals of this proposal; poor data quality from Hall A would directly affect the level at which the nuclear correction uncertainties are constrained. Conversely, even an infinitely accurate result from E97-110 would not help in constraining the nuclear correction uncertainty. For this, at least two neutron results *of comparable accuracy* but using different nuclear targets are needed. This condition is provided by the experiment E97-110 and proposal PR05-111 as discussed in the previous section.

To address this particular PAC issue, we have also modified our proposal to emphasize the importance of measuring the deuteron GDH sum itself at very low Q^2, without reference to any of the subsequent neutron results. Data on the deuteron sum is important to provide checks (without nuclear corrections) of the first calculations [5, 6, 7, 8] on the deuteron from χpT and lattice QCD. Also, this data will shed light on the fascinating cancellation of super and sub-threshold contributions to the deuteron GDH sum. This aspect of the proposal stands on its own and is, we believe, important enough in itself to justify an experiment.

Beam and target polarizations.

PAC 28 issue:*The beam and target polarizations used in the proposal might be too high and safer values of 75% and 30% have been assumed respectively.*

For this proposal update, we assume a target polarization value of 30%, as initially suggested by the TAC. However, 80% beam polarization is assumed, since more than 85% polarization is now consistently achieved by the source.

Scheduling Considerations

We discuss here several reasons which make it prudent to resubmit this proposal at this time. Experiment E03-006, the measurement of the GDH integral on the proton at low Q^2, is scheduled to run from February to May 2006 in Hall B. For that experiment, the polarized target and a new Cerenkov detector will be specially installed in the CLAS, both of which we also require. We require no other installation.

Running these two experiments sequentially will yield benefits for both the proton and deuteron analyses. All experts will be on site and no commissioning will be necessary for E05-111, resulting in a shorter runtime and higher data quality. The proton and deuteron run can be analyzed in parallel by the same analysis group, saving manpower. And the calibration of the detectors, and target polarization analysis will be simplified.

Most importantly, this experiment can utilize beam time in April-May 2006 that will otherwise be wasted. Due to a beam energy conflict with other halls, the present Hall B schedule has 20 days not attributed to any experiment. Our proposed experiment is the only one that requires low beam energy, the polarized target, and which can accommodate the new small angle Cerenkov detector.

Since the previous PAC, we have optimized our beam time request to make better use of this available time slot. Discussions [9] with the Hall B leader indicate that our beamtime request should be compatible with the existing schedule. Within 20 PAC days, this experiment could take 12 days of data at 1.34 GeV and 8 days at 1.99 GeV. 1.5 more days of 1.99 GeV data could possibly be taken after the end of E03-006. We have chosen to slightly emphasize the 1.3 GeV data because it is the energy that provides the lowest Q^2 coverage of the Δ and first resonance region, (see Fig. 4). These contributions, especially the Δ, are expected to dominate the GDH sum. The purpose of the 1.99 GeV data is not to increase the Q^2 coverage but rather to cover the large ν contribution at low Q^2. It is thus necessary to make the GDH measurement as complete as possible. In order to perform the best possible measurement, ten further days at higher energy would have to be ran at the next opportunity. Since it is not possible to accomodate this highest energy in the near term schedule, we do not request this beam time.

1 Introduction

We present here a proposal for measuring the extended Gerasimov-Drell-Hearn (GDH) integral on the deuteron and neutron at low Q^2. In the following pages, we first define the GDH sum rule and briefly recall its theoretical basis. After a short review of GDH experimental status, we describe the extension of the GDH integral to finite Q^2. Then we discuss the motivations for a measurement at low Q^2. We will end this document describing the proposed measurement and the beam time required to meet our goal.

1.1 The Gerasimov-Drell-Hearn Sum Rule

The Gerasimov-Drell-Hearn sum rule for real photon scattering at $Q^2 = 0$ is a fundamental relation that relies on only a few general assumptions:

1. Lorentz and gauge invariance in the form of the low energy theorem of Low [10], Gell-Man and Goldberger [11].

2. Unitarity in the form of the optical theorem.

3. Causality in the form of an unsubtracted dispersion relation [12] for forward Compton scattering.

For a target of arbitrary spin $\mathcal{S}$, the sum rule [13] reads:

$$\int_{\nu_{th}}^{\infty} \frac{\sigma_P(\nu) - \sigma_A(\nu)}{\nu} d\nu \quad = \quad -4\pi^2 \alpha \, \mathcal{S} \left(\frac{\kappa}{m} \right)^2 \tag{1}$$

where σ_P and σ_A represent the cross section for photoabsorption with the photon helicity parallel or anti-parallel to the target spin in its maximal state. The integration extends from the onset of the inelastic region, through the entire kinematic range and is weighted by the photon energy ν. The target mass and anomalous magnetic moment are represented by m and κ respectively. Experimental data and theoretical bounds suggest that the integral converges [14], and the only assumption that might be open to question is the validity of the non-subtraction hypothesis.

Eq. (1) reflects the fact that the presence of an anomalous magnetic moment is a clear signature of internal structure. However, a very small anomalous magnetic moment does not necessarily imply that the particle is nearly point-like. The deuteron, in particular, has quite small κ due to the cancellation of proton and neutron anomolous magnetic moments, yet it has a large spatial distribution due to it's relatively small binding energy. If the GDH sum rule holds, then this cancellation must be also reflected in the integral side of Eq. (1). Arenhovel [15] points out the importance of the threshold photodisintegration channel in satisfying the deuteron GDH sum rule, concluding that the disintegration channel must be approximately equal in magnitude (but opposite in sign) to all other inelastic processes. This strong cancellation is a fascinating feature that demonstrates a subtle connection between the coherent nuclear behaviour at low energy and the incoherent reactions at large energy.

1.1.1 Experimental Status

A dedicated test of the proton GDH sum rule has been undertaken at the MAMI [16, 17] and ELSA [18] facilities, in the range $0.14 < \nu < 0.80$ GeV and $0.7 < \nu < 2.9$ GeV respectively. The combined data set [19], which includes a theoretical estimate of the unmeasured contributions to the integral, is approximately 215 ± 13 μb, in good agreement with the GDH sum rule prediction of 205 μb. At JLab, an experiment is scheduled for the fall of 2006 in Hall B to measure the GDH sum rule for the proton using a frozen spin target [20]. An experiment [21] was approved at SLAC, specifically to investigate the convergence of Eq. (1), but it is not expected to run due to the termination of the SLAC ESA nuclear program. The question of convergence can, however, be addressed in part with the 12 GeV upgrade of JLab.

Neutron data from a polarized LiD target have been measured in the range $0.8 < \nu < 1.8$ GeV. The resulting neutron GDH integral value [22] is in agreement with the GDH sum rule prediction within uncertainty, although the limited energy range necessitates a much greater reliance on model input than in the proton case. The measured range, in fact, contributes only 15% of the total integral, so future results [23] extending the energy coverage below 0.8 GeV will be awaited eagerly. For an overview of the recent experimental results, and more global analysis, see refs. [24, 25, 26].

The deuteron data mentioned above will also be used to investigate the deuteron GDH sum rule directly [22, 23], and future experiments are planned to extend the deuteron energy range, both at Hiγs [27, 28] and at LEGS [29, 30].

At very low momentum transfer, the GDH sum rule can be tested by measuring the Q^2-dependence of the extended GDH sum, (see section (1.2)), and extrapolating to the real photon point. Experiment E97-110 [2] will be able to use this technique for ^{3}He and the neutron. In Section 2.5, we discuss extrapolation of the data from this proposed experiment to test the neutron GDH sum rule. This data will have very different systematic uncertainties from E97-110 for the extracted neutron, and these complementary data sets should provide high confidence in the neutron results.

1.2 The Extended GDH Sum Rule

Anselmino *et al.* [31] pointed out the connection between the GDH sum rule at $Q^2 = 0$ and the Bjorken sum rule [32] at infinite momentum transfer. They suggested that by extending the real photon GDH sum rule to finite Q^2, we may probe the transition from perturbative to non-perturbative QCD. Many possible generalizations of Equation (1) to finite Q^2 have been proposed (see [33]), each differing in the choice of the virtual photon flux, and on the way the spin structure function g_2 is included.

We focus here on the extension proposed by Ji and Osborn [34] because it generalizes not only the integral side of Equation (1) but the full sum rule. Hence, it retains the predictive power that is lost with other definitions. For an arbitrary hadronic target it is written:

$$\overline{S_1}(0, Q^2) \quad = \quad \frac{8}{Q^2} \int_0^{1-\epsilon} g_1(x, Q^2)\, dx$$

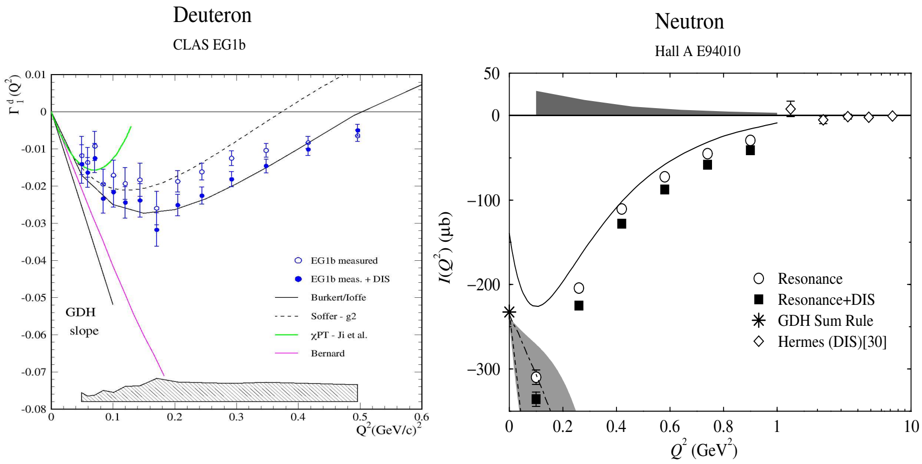

Figure 1: Q^2 evolution of the GDH integral on the deuteron and neutron.

$$\equiv \frac{8}{Q^2}\overline{\Gamma}_1 \tag{2}$$

Here g_1 is the familiar spin structure function, S_1 is the forward Compton amplitude, and the overbar represents exclusion of the elastic contribution. It is straightforward to show [34] that the GDH and Bjorken sum rules are limiting cases of this relation.

The forward Compton amplitudes can be evaluated [5, 6, 7, 8] in Chiral Perturbation theory at low Q^2, or via the higher twist expansion at large Q^2. Eventually, lattice QCD, which is particularly well suited for the spin structure functions, should provide calculations at any Q^2.

1.2.1 Experimental Status

The extended GDH integral has been investigated [35, 36, 37] in DIS using multiple targets at several different laboratories, but JLab has become the vanguard of low and intermediate Q^2 measurements. In particular, E94-010 measured the GDH integral on the neutron [38] and ^{3}He [39] down to Q^2 = 0.1 GeV^2, while in Hall B, the EG1 collaboration [40, 41, 42] performed similar studies on the proton and deuteron down to 0.05 GeV^2.

The PAC in recent years has recognized the importance of extending these measurements to the lowest possible Q^2, approving E97-110 with A$^-$ and E03-006 with A rating. The Hall A experiment used a ^{3}He target down to a momentum transfer of 0.02 GeV^2 in order to test χPT and the GDH sum rule for the neutron and for ^{3}He. It is expected that the most difficult part of that analysis will be to understand the nuclear corrections at low Q^2 well enough to extract the neutron. In Hall B, experiment E03-006 is scheduled to run in Spring 2006, using a polarized NH$_3$ target down to Q^2 = 0.01 GeV^2. E03-006 will determine g_1 from an absolute (polarized) cross section measurement, thereby eliminating the significant systematic uncertainty that arises from the target dilution factor. To this end, a new Čerenkov counter is being installed in one sector of CLAS to improve the efficiency at small angles. E03-006 will take data at beam energies of 2.6, 1.9, 1.3 and 1.0 GeV, with a short run at 0.8 GeV to study radiative corrections.

Recent JLab results are shown in Figure (1), while a more comprehensive overview of the experimental status is presented in Table (1). We stress that for all Q^2 regions, a rigorous comparison has been made using both ^{3}He and deuteron targets to gain access to the neutron, thus ensuring a full understanding of the the neutron extraction systematics. Presently, only ^{3}He has been used to access the neutron spin structure at very low Q^2, where the systematic uncertainty from extraction is expected to grow significantly.

Table 1: This table lists neutron structure measurements both existing and planned. While systematically done at large Q^2 and for the elastic reaction, the ^{3}He/Deuteron cross-check is missing at low Q^2 for the spin structure functions where it is most important. An asterix indicates the expected Q^2 coverage for on-going or future experiments.

Observable	**D target** Experiment	**D target** Q^2 in GeV^2	**^{3}He target** Experiment	**^{3}He target** Q^2 in GeV^2
g_1^n & Γ_1^n at large Q^2	SLAC E143 (1995)[43] SMC (1998) [35] SLAC E155 (2000)[44] HERMES (2003) [45] JLab EG1 (2003) [41] JLab SANE [46]	$< Q^2 >= 3$ $< Q^2 >= 10$ $< Q^2 >= 5$ $1.5 < Q^2 < 15$ $0.05 < Q^2 < 5$ $2.5 < Q^2 < 8.5$*	SLAC E142 (1996)[47] SLAC E154 (1997) [48] HERMES (1998) [37] JLab E99-117 (2004) [49] JLab E01-012 [50]	$< Q^2 >= 2$ $< Q^2 >= 5$ $1.5 < Q^2 < 15$ $2.7 < Q^2 < 4.8$ $1 < Q^2 < 4.0$
g_2^n & Γ_2^n at large Q^2	SLAC E143 (1995)[43] SLAC E155(2000) [44] JLab SANE [46]	$< Q^2 >= 3$ $< Q^2 >= 5$ $2.5 < Q^2 < 8.5$*	SLAC E142. (1996) [47] SLAC E154 (1997) [51] JLab E99-117 (2004) [49]	$< Q^2 >= 2$ $< Q^2 >= 5$ $2.7 < Q^2 < 4.8$
Γ_1^n at low Q^2	SLAC E143 (1995)[43] HERMES (2003) [45] JLab EG1 [42] JLab RSS [52]	$0.5 < Q^2 < 1.2$ $1.5 < Q^2 < 15$ $0.05 < Q^2 < 5$ $< Q^2 >= 1.3$	HERMES (1998)[37] JLab E94-010 (2002) [38] JLab E97-103 (2005) [53]	$1.5 < Q^2 < 15$ $0.1 < Q^2 < 0.9$ $0.57 < Q^2 < 1.34$
Γ_2^n at low Q^2	JLab RSS [52]	$< Q^2 >= 1.3$	JLab E94-010 (2002) [38] JLab E97-103 (2005) [53]	$0.1 < Q^2 < 0.9$ $0.57 < Q^2 < 1.34$
Γ_1^n, nearly real photons	/		JLab E97-110 [2]	$0.02 < Q^2 < 0.3$
Γ_2^n, nearly real photons	/		JLab E97-110 [2]	$0.02 < Q^2 < 0.3$
G_M^n	DESY (1973)[54] SLAC NE11 (1992)[55] Bates (1993)[56] NIKHEF (1994)[57] ELSA (1995)[58] MAMI (1998)[59] MAMI (2002)[60] JLab E94017 (2005)[61]	$0.7 < Q^2 < 3$ $1.8 < Q^2 < 8.9$ $0.11 < Q^2 < 0.26$ $Q^2 = 0.58$ $0.13 < Q^2 < 0.61$ $0.2 < Q^2 < 0.8$ $0.07 < Q^2 < 0.9$ $\sim 0.5 < Q^2 < 5$	Bates (1994)[62] JLAB E95001 (2000)[63, 64]	$Q^2 = 0.19$ $Q^2 = 0.1 - 0.6$
G_E^n	DESY (1971) [65] DESY(1973)[54] SACLAY (1990)[66] Bates (1994)[67] MAMI (1999)[68] NIKHEF (1999)[69] MAMI (1999)[70] Quadrupole F.F. data (2001)[71] JLab E93026 (2001)[72] JLab E93-038 (2003)[73] MAMI (2005) [74] JLab E04-110 [75]	$0.19 < Q^2 < 0.54$ $0.7 < Q^2 < 3$ $0.04 < Q^2 < 0.70$ $Q^2 = 0.26$ $Q^2 = 0.15$ $Q^2 = 0.21$ $Q^2 = 0.34$ $0. < Q^2 < 1.63$ $Q^2 = 0.5$ $Q^2 = 1.45$ $0.3 < Q^2 < 0.8$ $Q^2 = 4.3$*	MAMI (1994)[76] MAMI (2003) [77] JLab E02-013 [78]	$< Q^2 >= 0.31$ $< Q^2 >= 0.67$ $1.3 < Q^2 < 3.4$*

2 Motivation

In the previous section, it was pointed out that the extended GDH sum can be measured and compared to calculations at any momentum transfer. Studying the Q^2 evolution of the sum illuminates the transition from the partonic to hadronic descriptions of the strong interaction, so these measurements have been an important focus of the JLab experimental program [2, 1, 24, 38].

We propose to extend our knowledge of the deuteron and neutron Q^2 evolution to the lowest possible JLab momentum transfer ($0.015<Q^2<0.2$ GeV^2) using an ND_3 target and the CLAS detector as upgraded for experiment E03-006. Apart from the target, this experiment would have an identical setup and similar beam energy requirements to E03-006. In this section, we will discuss the benefits of performing this experiment.

2.1 The Deuteron Extended GDH Sum at low Q^2

The deuteron has been used extensively to provide access to the neutron, but the deuteron extended GDH sum rule is an intriguing quantity in its own right. It has been argued [79] that measuring the deuteron GDH integral as a function of Q^2 will provide a significant test of the present theoretical understanding of the properties of few-body nuclei. As in the case of real photon scattering, the disintegration channel is expected [15, 79, 80] to play a crucial role, providing a large negative contribution that very nearly cancels the sum of all contributions from meson production. Arenhovel *et al.* predict that the electrodisintegration channel contribution is largest for $Q^2 \approx 0.2$ fm^{-2} which is near the low kinematic range of this proposal (see Fig (2)).

We acknowledge the experimental challenge of separating the elastic scattering contribution from the breakup channel given the CLAS energy resolution. However, for $Q^2 > 0.08$ GeV^2, the threshold region is dominated by the quasielastic reaction, and the electro-disintegration channel is a small contribution in comparison, as displayed in Figure (3). For these kinematics, the main issue will be subtraction of the elastic radiative tail from the quasielastic data. This has been accomplished in previous EG1 experiments at similar Q^2 which relied on precise quasielastic data for accurate determination of the beam and target polarization. We conclude that the subthreshold contribution to the deuteron sum can be measured in CLAS without issue down to at least 0.08 GeV^2.

We now describe how we will address the resolution issue at the lowest Q^2 of this proposal. The electro-disintegration and quasi-elastic contributions have been modeled in detail [81, 82, 83], and the elastic contribution is well known. The models can be convoluted with the CLAS resolution to reproduce the measured cross sections below pion threshold. In analogy to the unfolding process used in radiative corrections, we can then deconvolute the individual channel contributions. We note that such a resolution unfolding technique has been used previously [84, 85] for measurements of the deuteron electrodisintegration channel with detector resolutions of 10 MeV. An explicit example of this technique is discussed in detail in Appendix A.

We point out that there does not exist at this time any experimental setup which is suitable to measure the GDH integral over the entire kinematic range. It has been necessary in the case of the real photon GDH sum rule, for example, for several different

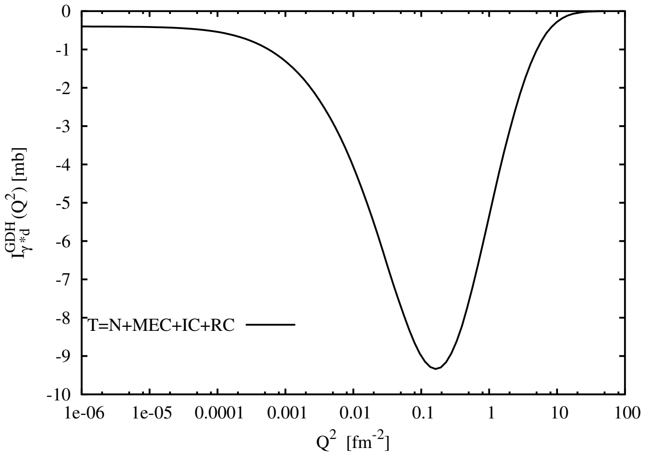

Figure 2: Generalized GDH integral as a function of Q^2 for deuteron electrodisintegration $d(e,e')np$ from Ref. [15].

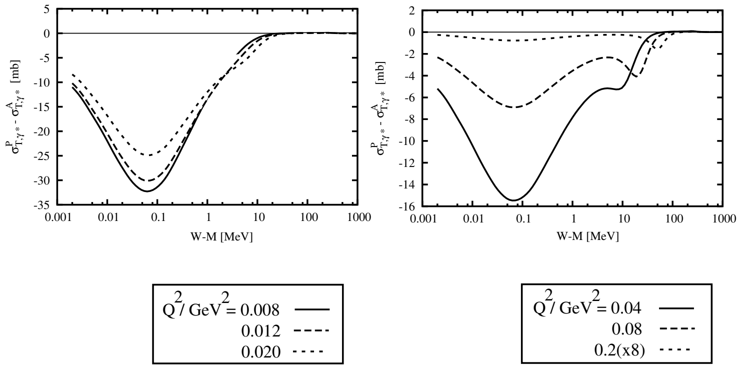

Figure 3: Transverse spin asymmetry of $d(e,e')np$ for various values of Q^2. The small contribution above 10 MeV at large Q^2 is the quasi-elastic reaction, which dies off at lower momentum transfer. Calculations based on Argonne V_{18} potential including interaction and relativistic effects. Plot from Ref. [15].

experiments to each examine some portion of the integral. With this in mind, the contribution above threshold, which may be measured without complication in CLAS, is a valuable part of the total integral. The systematic uncertainty and model dependence associated with the resolution unfolding technique discussed above can be eliminated by measuring the subthreshold contribution with a different experimental setup. Such a measurement at forward angle would not require very much beamtime. We propose to make such a measurement in Hall C. The HMS spectrometer provides sufficient resolution and the rates are high enough that the region of interest can be mapped out in only a few days. For further details see ref. [86].

2.2 Testing χPT and Lattice QCD

The JLAB results on GDH at intermediate Q^2 [87, 40, 41, 38] triggered discussions showing a large interest for pushing measurements to smaller Q^2. It is clear from the neutron results on spin polarizabilities [87], especially for the longitudinal-transverse polarizability δ_{LT}, that more theoretical work is needed to understand the data and the transition from partonic to hadronic degrees of freedom of the strong interaction. Similarly, preliminary results from the 1.6 GeV EG1 proton and deuteron runs show consistency with χPT calculations as high as $Q^2 = 0.1$, but only within the large statistical and systematic uncertainties of the data (see Fig. (1)).

χPT calculations are the only rigorous computations available presently for $\Gamma_1(\mathrm{Q}^2)$ at low momentum transfer [88, 89, 90]. However, there are several theoretical issues regarding the accuracy and domain of application of χPT. For example:

1. The prediction for the slope of $\Gamma_1(\mathrm{Q}^2)$ at the photon point changes sign when going from leading order to next to leading order, so it is not obvious that the first few terms of the chiral expansion are sufficient for establishing a reliably convergent χPT prediction.
2. The importance and method of inclusion of the resonances in χPT calculations is still uncertain.
3. The Q^2 range of applicability of χPT needs to be tested.

Providing data at the lowest possible Q^2 is crucial to constrain the χPT calculations and to address these issues. First χPT and lattice QCD calculations on nuclei are becoming available [5, 6, 7, 8], without the issue of nuclear corrections. Since the deuteron is the simplest non-trivial nucleus, it is the natural place to test these predictions.

2.2.1 Generalized Spin Polarizabilities

The spin polarizabilities are fundamental observables that characterize nucleon structure and present one of the best tests of χPT calculations at low Q^2. Like the GDH sum, they are related to integrals of the nucleon excitation spectrum and rely on the same basic theoretical assumptions. At the real photon point, the electromagnetic polarizabilities reflect the nucleon's response to an external electromagnetic field. The generalized polarizabilities represent an extension of these quantities to virtual photon

Compton scattering at finite Q^2. The polarizabilities are expected to converge faster than the first moments and thus reduce the dependence of measurements on extrapolations to the unmeasured regions at large ν.

2.3 The Neutron Extended GDH Sum at Low Q^2

Neutron studies often challenged our understanding of nucleon structure. Although the GDH sum rule seems to be valid for the proton, the neutron sum rule is not yet verified. It is worthwhile to note that the most recent estimate based on multipole analysis, the MAID model, violates the sum rule for the neutron, which is consistent with the earlier estimates of Karliner [91] and then Workman and Arndt [92]. In short, the verification of the sum rule on proton does not preclude its violation for a neutron target. Aside from this, the neutron is essential for access to the Bjorken sum (discussed in Section 2.6).

The low-Q^2 domain for the neutron is under investigation at JLab (via ^{3}He) [2]. However, the neutron extraction at low Q^2 is complicated due to the increasing importance of nuclear effects [3, 15]. An experiment using another target for which the nuclear corrections, and the related systematic uncertainties, are completely different is crucial to ensure a full understanding of the neutron extraction systematics.

In Appendix B, we recall the procedures used for neutron extraction in the DIS region and, for integrated quantities, in the intermediate Q^2 domain. To summarize the appendix, the extraction of neutron moments can be performed with a PWIA method (convolution model), which can be approximated to a good level by the DIS method accounting simply for the effective polarization of the nucleons within the nucleus. The magnitude of the correction grows at low Q^2, where there is no further justification of the use of effective polarizations beside the fact that the results are close to the PWIA method. Since PWIA is known to be unreliable at low Q^2, both the convolution model and the effective polarization methods cannot be used *a priori* at low Q^2. More sophisticated models or calculations have to be used that account for nuclear effects, such as final state interactions, meson exchange currents, EMC effects or Pauli-blocking. Work is on going to include final state interactions that are believed to be the most important at low Q^2 [93]. Such work must be compared to experimental results from both the deuteron and ^{3}He to establish the reliability of neutron extraction.

It is important to realize that, at present, there is no calculation of the nuclear corrections below $Q^2 = 0.1$ GeV^2. Consequently, the uncertainty of nuclear extraction in this region is unknown. An estimate may be provided by comparing the results obtained using the effective polarization method and the convolution method. For ^{3}He, the results differ by approximately 5% for $Q^2 > 0.1$ GeV^2, and increase to 10% at 0.1 GeV^2 [4]. In the case of the deuteron, the uncertainty is claimed [3] to be no greater than 3% for $0.1 < Q^2 < 2.0$ GeV^2. Consequently, we may expect a slightly smaller uncertainty for deuteron below 0.1 GeV^2. The estimate of the uncertainties is treated in detail in Section 4.1.

2.4 Complementarity of this proposal and E97-110

Measurements at forward angle can be difficult due to increasing backgrounds and the growing importance of radiative corrections. This is especially true for the GDH sum for which the elastic radiative tail near pion threshold has to be well understood for proper subtraction. We note that the analysis of the lowest Q^2 data of experiment E97-110 will be complicated by the miswiring of the septum magnet used to detect the forward electrons for part of the Hall A run. This problem will increase the systematic uncertainties on the lowest Q^2 points as discussed in the 2003 Hall A status report [94].

It is not the goal to the this proposal to improve on the measurement done in Hall A, aside from providing the necessary data to have confidence in the neutron extraction method. However, we can reach a comparable precision for the lowest Q^2 points, where the neutron extraction method starts to be unreliable and where a cross check is most valuable. Also, due to the low angle coverage of the new CLAS Cerenkov detector, and to the fact that the ^{3}He experiment encountered technical difficulties, this experiment will provide better accuracy for the very low Q^2 points as illustrated in Fig. (7).

2.5 Extrapolation to the Real Photon Point

Measuring the GDH sum rule by extrapolation from nearly real photon data would provide a completely independent cross-check of the techniques presented in Section 1.1.1. In particular, measuring the GDH sum at the photon point demands detection of hadrons while at finite Q^2, a simpler inclusive measurement is sufficient. We present three possible scenarios that may be encountered in an attempt to extrapolate to the real photon point:

1. The data is found to exhibit linear behaviour at low Q^2. In this case it will be straightforward to extrapolate to $Q^2 = 0$.
2. We find a more complicated dependence with Q^2 that agrees with χPT calculations. We may then utilize the χPT calculations to guide the extrapolation. (We note, however, that the available calculations all predict linear behavior at present.)
3. The data exhibits a complicated Q^2 dependence *and* disagrees with χPT. This would make the extrapolation difficult, but is perhaps the most interesting and exciting possibility as it would require a serious re-examination of the fundamental precepts of χPT.

We discuss the systematic uncertainty of such an extrapolation in Section 4.6.

2.6 The Bjorken Sum at Low Q^2

In combination with the E03-006 proton data, we can form the difference $\Gamma_1^p - \Gamma_1^n$ which is predicted at the photon point by the GDH sum rules on the proton and the neutron. This is the best quantity to extrapolate to the photon point since its evolution is smoother than the individual nucleon integrals due to the partial cancellation of the resonance contribution [95]. For the same reason, the Bjorken sum is also calculable in χPT with a range of applicability that is expected to be larger than for the GDH integral. In fact, the upper Q^2 limit of χPT calculations for the Bjorken sum is expected to approach the range of applicability of the Higher Twist Expansion. At large Q^2, the Bjorken sum is the only moment for which the absolute value is predicted, in contrast for example to the Ellis-Jaffe sums. Furthermore, its Q^2 behavior at leading twist is simpler and does not involve gluon distributions because only non-singlet coefficients enter in the operator product expansion. Finally, since the Bjorken sum is both a moment and a flavor non-singlet quantity, it is particularly suitable for Lattice QCD calculations. Hence, it appears that the Bjorken sum is the perfect quantity to provide benchmark measurements for the three theoretical frameworks that are used to understand the transition from hadronic to partonic degrees of freedom. It is therefore a most important object to measure accurately on the entire Q^2 range.

Performing this proposed experiment under the same circumstances as E03-006 will minimize the point to point systematic errors. In fact, the Q^2-evolution is often more important than the absolute value of the sum since calculations often deal only with the Q^2-behavior. Examples are analyses within the Operator Product Expansion framework (extraction of higher twists [96]) or comparison to χPT. Experiments done on both nucleons under the same experimental conditions will provide the best condition for an accurate comparison to theory.

2.7 Experimental Considerations

Measurements of inelastic reactions at low Q^2 are in general harder to carry out. This is due to large radiative corrections and increasing backgrounds. A cross check of E97-110 and this proposed experiment, using completely different targets and detection systems, is not a motivation in itself. However, it would provide additional confidence in the measurements. It is also worthwhile to note that the CLAS detector will redundantly measure several kinematic bins, but with different angles and beam energy (see overlap in Fig. (4)). There will therefore be different backgrounds and radiative corrections, and will provide an important self cross-check of our measurement.

3 Proposed Measurement

3.1 Kinematics

We propose to cover the kinematic range displayed in Figure (4), which requires two incident beam energies: 1.337 and 1.987 GeV. This will allow us to evaluate the Q^2-evolution of the GDH integral from 0.015 to 0.2 GeV^2. A short run with a 0.8 GeV beam, not shown in the figure, will help reduce the systematic uncertainties arising from the radiative corrections. In Figure (4), any region where the elastic tail is expected to be prohibitively big has been excluded, leading to the cutoffs at low Q^2.

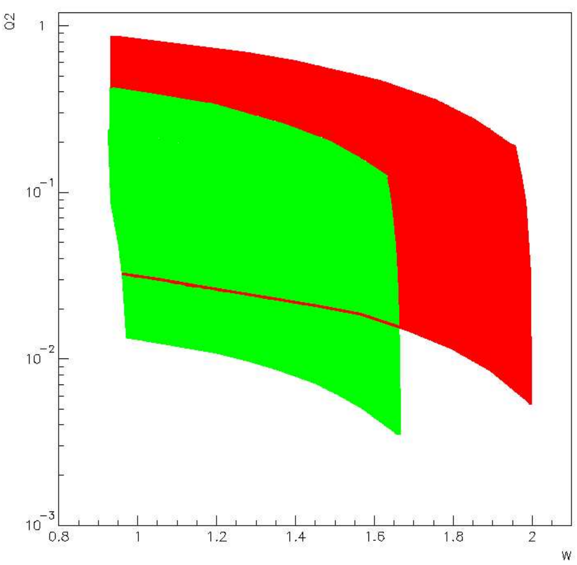

Figure 4: Proposed kinematic coverage for two incident energies: 1.337 and 1.987 GeV. Not shown is the short 0.8 GeV run necessary for radiative correction studies.

3.2 Experimental Setup

In order to perform an absolute cross section measurement, we plan to use a modified setup which includes the new Čerenkov counter that is being commissioned for E03-006. This detector is specifically designed for the outbending field configuration which is necessary to reach the desired low Q^2. This new detector will have a very high electron detection efficiency (of the order 99.9%) to allow the measurement of the absolute cross section with minimal corrections and a high pion rejection ratio (of the order 10^{-3}). The other components of CLAS will be in standard configuration.

We will use the JLab/UVA ND_3 polarized target [97] used in previous CLAS spin-dependent measurements. This target exploits the Dynamical Nuclear Polarization (DNP) technique to polarize the material which is maintained in a liquid helium bath at 1 K and in a 5 Tesla longitudinal field. This system operated successfully in previous CLAS runs, providing typical deuteron polarizations of 30%. The deuteron polarization will be monitored online by an NMR system and then extracted offline by the analysis of quasi-elastic scattering events which are recorded simultaneously with the inelastic events thanks to the large CLAS acceptance. This method provides a more precise measurement of the product of beam and target polarization than does the individual measurements of the electron polarization using the Moller polarimeter and the target polarization using the NMR. The polarized target will be retracted by 1 m upstream to increase the acceptance at low Q^2, by reducing the minimal angle for the scattered electron, allowing us to reach $Q^2 = 0.015$ GeV^2. The target will contain two ^{12}C inserts of differing thickness, and an empty cell in addition to the ND$_3$ for background measurements. Each of these cells can be moved into the beam via remote control. In addition we will use a solid nitrogen target to check the nitrogen contribution. There will be two ND$_3$ cups 1 cm, and 0.5 cm in length respectively. Both will be 1.5 cm in diameter.

We will exploit the highly polarized JLab electron beam. Previous experiments have shown that a typical polarization of 85% can be expected. However, we will assume 80% in this proposal. Beam currents of 1-2 nA will be used. In these conditions, no significant heating of the target material takes place. The beam will be rastered over the target surface to minimize radiation effects, using the existing Hall B raster. Due to the low beam current and the rastering, radiation damage to the target material will be limited, and annealing will be required only once per week. The beam polarization will be measured by the Hall B Moller polarimeter, while as mentioned above the final value of the product of beam and target polarization will be extracted from the quasi-elastic data.

We note that the experimental setup is the same as for experiment E03-006, apart from the target cell used. E03-006 is scheduled to run in 2006, and requires installation of the polarized proton target and a new Cerenkov detector, currently under construction at INFN. If the experiment described in the present proposal ran just after or during E03-006, one would take advantage of this to minimize both the beam down time and the use of manpower in Hall B.

We will trigger CLAS by requiring a coincidence between the electromagnetic calorimeter and the new INFN Cerenkov counter, which will be installed in only one sector. We will not accept electron triggers from other sectors of CLAS. In fact, in order to maximize our useful data rate for scattered electrons, we will turn off the other five sectors of CLAS.

3.3 Extraction of g_1

The use of absolute cross section differences is a robust way of extracting g_1 because the unwanted unpolarized contribution cancels out. This extraction technique meets its full interest with the ND$_3$ target where the amount of unwanted (non-deuteron) target material is necessarily large.

The spin structure function g_1 is related to the spin-dependent cross sections via:

$$g_1 = \frac{MQ^2}{4\alpha^2} \frac{y}{(1-y)(2-y)} \left(\Delta\sigma_{\parallel} + \tan\frac{\theta}{2} \Delta\sigma_{\perp} \right) \tag{3}$$

Here $\Delta\sigma_{\parallel} = \sigma^{\uparrow\Uparrow} - \sigma^{\downarrow\Uparrow}$, and $\Delta\sigma_{\perp} = \sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}$ with the first superscript indicating the electron spin, while the second refers to the target spin orientation. The Hall B polarized target can be polarized only in the longitudinal direction at present, so there will be some error introduced by neglecting the perpendicular term in Eq. (3). We have estimated this effect by evaluating the contribution of $\Delta\sigma_{\perp}$ to g_1 using a fit to world data [98]. Figure (5) reveals that at the proposed kinematics, the effect of neglecting

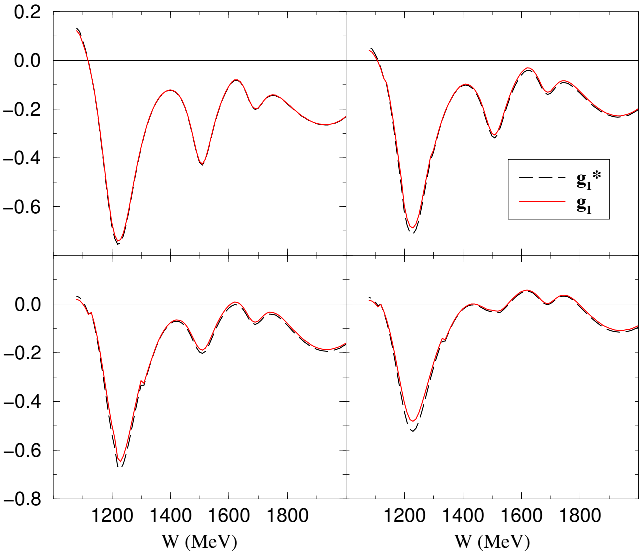

Figure 5: The effect of neglecting $\Delta\sigma_\perp$ on g_1. In the plots, g_1^* represents Eq. (3) with $\Delta\sigma_\perp$ set to zero. Top Left: $Q^2 = 0.01$ Top Right: $Q^2 = 0.05$ Bottom Left : $Q^2 = 0.1$ Bottom Right : $Q^2 = 0.2$

the $\Delta\sigma_\perp$ contribution is indeed quite small. Neglecting $\Delta\sigma_\perp$ entirely results in a maximum 5% difference in Γ_1 at our highest Q^2, and falls to less than 1% at $Q^2 = 0.01$ GeV^2. (See Table (2)). These results are in general agreement with the EG1B systematic analysis [99]. The systematic effect will be smaller than this of course and will depend on the accuracy of the model used to estimate the perpendicular contribution. Following the EG1B analysis, we assume conservatively 50% uncertainty on the model input, which can be reduced with more careful studies in the future.

Q^2 (GeV^2)	Γ_1^*	Γ_1	Difference
0.01	-0.0070620	-0.0070220	0.6%
0.05	-0.0298287	-0.0292262	2.1%
0.10	-0.0456892	-0.0442065	3.4%
0.20	-0.0489075	-0.0464575	5.3%

Table 2: Uncertainty in g_1 due to the lack of transverse data. Γ_1^* represents the first moment of Eq. (3) evaluated [98] assuming $\Delta\sigma_\perp = 0$.

Energy (GeV)	days	current (nA)
0.8	0.3	1
1.337	12	1
1.987	8 +1.5	2
Total	19.5	

Table 3: Beam Request Summary.

3.4 Rates and Beam Time Estimate

Ostensibly, the rates and beam time request of this proposal will be similar to approved experiment E03-006. We must however adjust for the variation of rates due to the differing targets and attainable target polarizations, and also for improvements in various JLab instrumentations.

The expected counting rates [1] for inelastic scattering from proton were estimated assuming: a W bin of 20 MeV, a Q^2 bin of 0.01 GeV^2, a polar angular interval $\Delta\phi$ of 18° for one module of the Čerenkov detector, a beam current of 1 to 2 nA depending on the energy, and beam energies of 1.337 and 1.987 GeV. We assumed a minimum electron detection angle of 5 degrees. A minimum energy for the outgoing electron of 300 MeV was also assumed in integration to obtain the GDH sum. The unpolarized inclusive electron scattering cross section was calculated based on a parameterization of the two structure functions F_1 and F_2 [98].

We assume a target polarization of 30%, a beam polarization[*] of 80%, and an improved DAQ rate of 6 khz. Taking into account the ND$_3$/NH$_3$ target nucleon ratio we arrive at the beam time estimate displayed in Table (3). The very short run at 0.8 GeV is to ensure we control our radiative corrections. This energy setting will be dedicated to an unpolarized measurement of the elastic radiative tail and as such requires a small amount of beam time.

The expected precision can be seen in Figs. (6) and (7). The systematic uncertainty arising from nuclear corrections assumed in Fig. (7 is described in Section 4.1. A comparison of neutron results extracted from D to those extracted from ^{3}He would give an estimate on the size of the nuclear corrections and hence would constrain to the same level the accuracy of the neutron extraction procedure.

Let us note that this number is relevant only to the particular problem of extracting neutron. Nuclear models themselves will be further constrained by directly comparing our doubly polarized data to model predictions.

3.5 Change to the Proposed Kinematics Coverage

In the previous proposal presented to PAC 28, we requested three beam energies (1.1, 1.6 and 2.2 GeV) with a total request of 30 days of beam time.

For this proposal we have optimized our beam time request to accomodate the constraints of the near term Hall B schedule. The 20 requested days can be scheduled

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[*] 85% beam polarization is now routinely achieved.

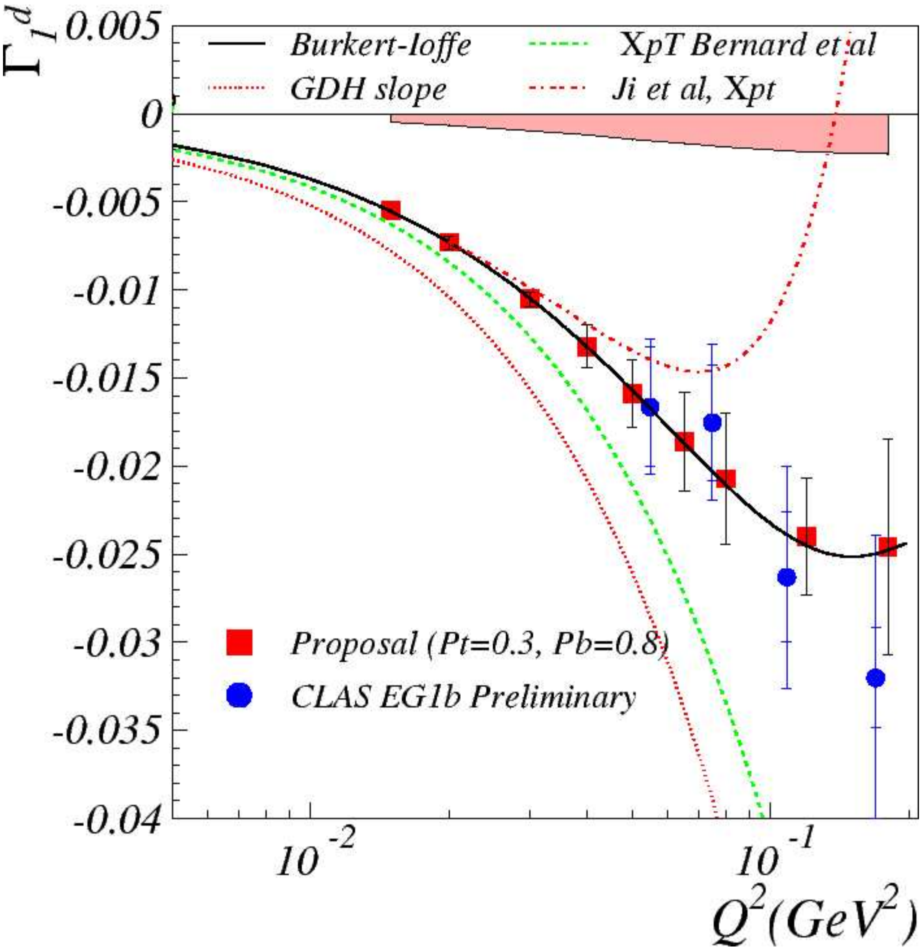

Figure 6: Expected precision of deuteron Γ_1. The band represents the systematic uncertainty, while the error bars on the points are statistical only. The curves from Bernard *et al.* [88, 89] and Ji *et al.* [34] are χPT calculations. The curve from Burkert-Ioffe [100] and Soffer-Teryaev [101] are phenomenological models. The preliminary EG1B data [42] are shown for comparison.

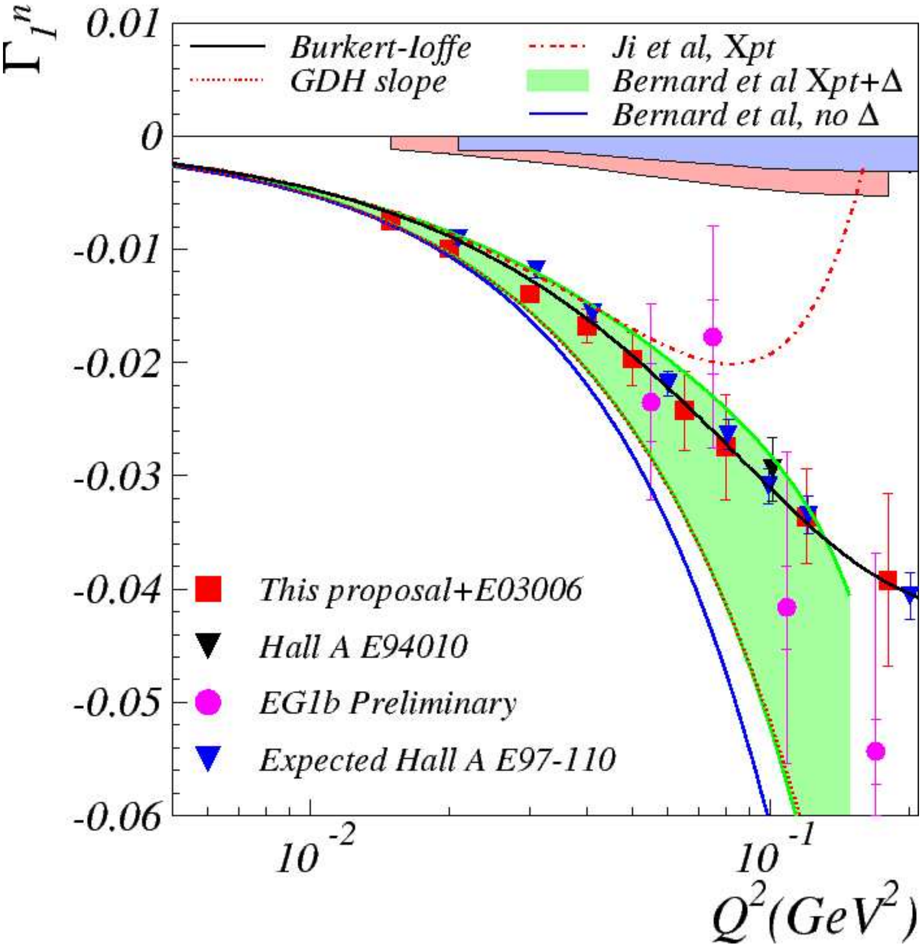

Figure 7: Expected precision of neutron Γ_1. The error bar contains both statistical and systematic uncertainty. The projected uncertainties for the present proposal include the error on the proton measurement. The relevant domain for comparing neutron extracting from ^{3}He and D is below $Q^2 \sim 0.1$, where the known method to extract the neutron becomes less reliable. The points at higher Q^2 are ancillary results coming from the higher beam energy runs necessary to expand the W coverage of the lower Q^2 points. See Fig. (6) for a description of theoretical curves.

to utilize beam time that will otherwise be wasted immediately after the completion of E03-006. The polarized target and small angle Cerenkov detector will be installed in CLAS at this time, and due to the other Hall energy selection, the incident energy will be quite low. In order to accommodate for the time and energy constraints, only two energies are now requested: 1.34 and 1.99 GeV. With these two energies, the lowest Q^2 angle is 0.015 GeV^2 instead of 0.010. The effect of not having a third higher energy affects the statistical accuracy of points at Q^2 greater than 0.04 GeV^2 and reduces the W integration limit. We note that for $Q^2 > 0.04$ GeV^2, it is the highest energies that are the most important to the statistical accuracy. This is because for a given Q^2, it is more efficient to gather data at high energy and small angles rather than lower energy and larger angle.

Figs. (12) and (13) in Appendix C show what we could achieve with 30 days of beam time and three energies as we previously proposed.

3.5.1 Overhead

We estimate 4 hours needed for the pass change. Two hours will be required each week for Moller polarimetry and/or target annealing. Assuming 50

Previous polarized target runs have demonstrated that the necessity to anneal the target has minimal impact on beamtime, as this procedure can be scheduled during weekly beam studies. Furthermore, the annealing procedure will be required less frequently due to the low current used in Hall B.

This brings the total requested beamtime including overhead to 20.1 days.

4 Systematic Uncertainties

4.1 Uncertainties on nuclear corrections

The relevant uncertainties on nuclear corrections come from two sources:

1. the uncertainty ΔM on the neutron extraction method itself.
2. the uncertainty on the input needed to provide the correction, e.g. the proton information.

The best estimate at present for ΔM comes from refs. [3] and [4] for D and ^{3}He, respectively. The authors have estimated the error by taking the difference between the full result of the convolution method and the simpler method of effective polarizations[†]. We note that these estimates do not account for other possible nuclear effects such as FSI or MEC. However, they are the only results available at the moment.

We denote by $\Delta M_D(Q^2)$ and $\Delta M_{He}(Q^2)$ the uncertainties coming from the method used for nuclear corrections for D and ^{3}He respectively. According to ref. [3], $\Delta M_D = 2\%$ at $Q^2 = 0.1$ GeV^2, and $\Delta M_D = -0.3\%$ at $Q^2 = 1$ GeV^2. For ^{3}He [4], $\Delta M_{He} = 8\%$ at $Q^2 = 0.1$ GeV^2 and $\Delta M_{He} = 4\%$ at $Q^2 = 0.25$ GeV^2. Their values are obtained for $Q^2 < 0.1$ GeV^2 by linear extrapolations.

[†] This is discussed in full detail in Appendix B.

4.1.1 Uncertainties using effective polarization method formulas.

In this section, we use the effective polarization method formulas to estimate the uncertainty on Γ_1^n due to nuclear corrections. For D, we have:

$$\Gamma_1^n = \left(\frac{2}{1-1.5\omega_d}\right)\Gamma_1^d - \Gamma_1^p \tag{4}$$

with $\omega_d = 0.05 \pm 0.01$.

For ^{3}He, we have:

$$\Gamma_1^n = \frac{\Gamma_1^{He} - 2P_p\Gamma_1^d}{P_n} \tag{5}$$

with $P_n = 0.86 \pm 0.02$ and $P_p = 0.028 \pm 0.004$

From the formulas above and assuming that the uncertainties add in quadrature, we have:

$$\Delta\Gamma_1^{n(D)} = \Bigg[\left(\frac{3\Gamma_1^d}{(1-1.5\omega_d)^2}\right)^2(\Delta\omega_d)^2 + \left(\frac{2}{1-1.5\omega_d}\right)^2(\Delta\Gamma_1^d)^2 \\ + \left(\Delta\Gamma_1^P\right)^2 + (\Delta M_D)^2\Bigg]^{\frac{1}{2}} \tag{6}$$

and

$$\begin{aligned}\Delta\Gamma_1^{n(He)} &= \Bigg[\left(\frac{1}{P_n}\right)^2(\Delta\Gamma_1^{He})^2 + \left(\frac{\Gamma_1^{He} - 2P_p\Gamma_1^p}{P_n^2}\right)^2(\Delta P_n)^2 \\ &+ \left(\frac{2P_p}{P_n}\right)^2(\Delta\Gamma_1^p)^2 + \left(\frac{2\Gamma_1^p}{P_n}\right)^2(\Delta P_p)^2 + (\Delta M_{He})^2\Bigg]^{\frac{1}{2}}\end{aligned} \tag{7}$$

where the uncertainties on $\Delta\Gamma_1^{He}$, $\Delta\Gamma_1^D$ and $\Delta\Gamma_1^p$ are systematic only. Their statistical counterparts are added in a similar way to the statistical uncertainties on $\Delta\Gamma_1^n$. The uncertainties $\Delta\Gamma_1^{He}$, $\Delta\Gamma_1^p$ and $\Delta\Gamma_1^D$ are given by the proposals E97-110 [2], E03-006 [1] and this document, respectively. $\Delta\Gamma_1^{He}$ has been modified according to the E97-110 report in the Hall A status report [94], to account for the increase of systematic uncertainties at the lowest Q^2 points due to the Hall A septum magnet mis-wiring. The systematic uncertainties due to nuclear corrections are show as a function of Q^2 in Figure 8. They correspond to the formulas above in which the contribution from $\Delta\Gamma_1^d$ and $\Delta\Gamma_1^{He}$ are set to zero.

4.1.2 Complementarity of ^3He and D in constraining nuclear uncertainties on neutron extraction.

Given the smallness of $\Delta\omega_d$ and (ΔM_D), we can write:

$$\Delta\Gamma_1^{n(D)} \simeq \sqrt{\left(\frac{2}{1-1.5\omega_d}\right)^2 \left(\Delta\Gamma_1^d\right)^2 + \left(\Delta\Gamma_1^P\right)^2} \tag{8}$$

For ^{3}He, $P_p \ll P_n$ and $\left(\Delta P_{n(p)}\right)$ are small. Consequently, we can write:

$$\Delta\Gamma_1^{n(He)} \simeq \sqrt{\left(\frac{1}{P_n}\right)^2 \left(\Delta\Gamma_1^{He}\right)^2 + \left(\Delta M_{He}\right)^2} \tag{9}$$

Ignoring the contribution from the measurements themself, $\Delta\Gamma_1^d$ and $\Delta\Gamma_1^{He}$, we obtain the approximate uncertainties on nuclear extraction only:

$$\Delta_{nuc}\Gamma_1^{n(D)} \simeq \Delta\Gamma_1^P \tag{10}$$

$$\Delta_{nuc}\Gamma_1^{n(He)} \simeq \Delta M_{He} \tag{11}$$

From these two approximations, it is clear that the dominant systematic uncertainty on nuclear corrections comes from two very different origins for D and ^{3}He. Given that the two uncertainties $\Delta_{nuc}\Gamma_1^{n(D)}$ and $\Delta_{nuc}\Gamma_1^{n(He)}$ are of the same order of magnitude, (see Fig. (8)), this demonstrates the excellent complementarity between neutron experiments done on D and ^{3}He.

This can be understood naively as follows:

- D is a the most simple non-trivial nucleus. Furthermore, p and n are loosely bound. On the other hand, the proton correction comes without suppression. Hence, it dominates the nuclear uncertainty.
- ^{3}He is a more complex nucleus in which the nucleons are more tightly bound. On the other hand, the proton correction is suppressed. Hence, the nuclear correction is dominated by the systematic uncertainty on the model.

4.2 Polarized cross section

One limiting factor in measuring quantities with the polarized target is the precise knowledge of target thickness. Measurements will be made after the experimental run to measure it at the % level (for example by melting the ammonia beads and measuring the volume of ammonia). The total luminosity will be also monitored by continuous measurement of the quasi-elastic cross section. Such measurement will be used as well to extract the product of the beam and target polarizations.

All in all, we expect a 5% systematic accuracy [102] on the unpolarized cross section measurement before radiative corrections, and 5% on the asymmetry. These two quantities are used to form the difference of polarized cross sections.

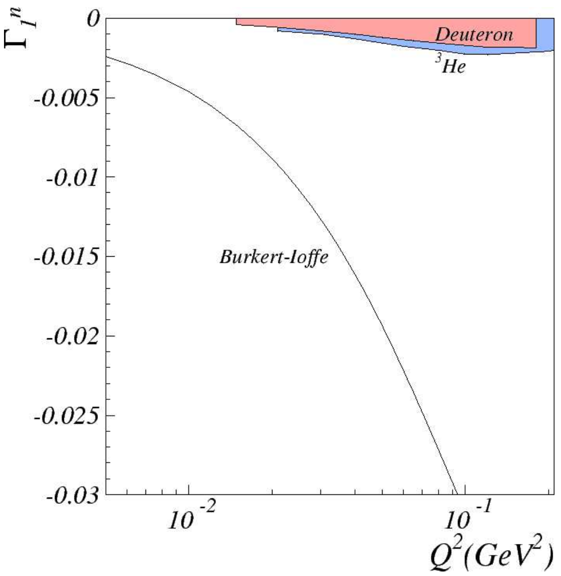

Figure 8: Systematic uncertainties due to nuclear corrections (dotted for D, plain for ^{3}He), are shown in function of Q^2.

4.3 Radiative corrections

Radiative corrections are needed to extract the Born cross section from the measured one. This procedure is well established for both unpolarized [103] and polarized [104] scattering.

At the low momentum transfer of this proposal, elastic radiative tails can limit a meaningful extraction of g_1 from background contamination. We expect to control the radiative tails systematics uncertainty from external radiative corrections by running with different target thickness (0.5 and 1 cm). Together with this systematic check, a short run at 0.8 GeV beam energy will allow to minimize the uncertainty on the total (internal and external) radiative tails. Finally, data from regions where the elastic tail is large (cross section a few time larger than the inelastic signal) will not be used in the analysis (see Fig. (4)). One of the main effect of the radiative corrections is to redistribute the events along the target excitation spectrum. Since we are interested by the integral over the excitation spectrum, the overall effect of the radiative corrections is somewhat reduced. All in all, we assume a systematic uncertainty of 5% or better.

The overlap of kinematic coverage from different incident energies (with different radiative corrections) will help ensure that we understand the systematic to this level.

4.4 Large W extrapolation.

An extrapolation to large ν is needed to account for the unmeasured high energy contribution. The uncertainty on the sum due to this missing part is not larger than 2%. This has been estimated in the following way: we evaluate the total sum Γ_1^d using the model of Burkert and Ioffe [100] which agrees well the JLab data taken at intermediate and large Q^2 (see for example [105]). The size of the unmeasured part of Γ_1^d is estimated using the Bianchi-Thomas parameterization [106] based on a Regge form constrained by the polarized world data. A 50% uncertainty on the magnitude of the missing part was taken as the uncertainty on the total sum. In the above calculation, the deuteron was formed using the proton and neutron predictions according to the formula:

$$\Gamma_1^D = \frac{\Gamma_1^p + \Gamma_1^n}{2/(1 - 1.5\omega_D)} \tag{12}$$

with $\omega_D \simeq 0.05$.

4.5 Other systematics effects

A large nitrogen background is present when ammonia polarized targets are used. This background is mostly unpolarized and cancels out in the difference of polarized cross sections. The slight remaining polarization of the ^{15}N will need to be corrected. We expect 1 to 2% uncertainty on the cross section due to this correction.

4.6 Extrapolation to $Q^2 = 0$

The expected errors on the GDH sum rule at the photon point can be estimated by extrapolating the measurement at our lowest Q^2 point using five[‡] available theory predictions normalized the data. The dispersion of the results gives some indication of the uncertainty due to extrapolation that we may expect. The lowest Q^2 point is well into the domain where all available calculations predict linear behavior. Thus, the uncertainty on the extrapolation is dominated by our experimental systematic.

Following this estimate, we expect a 9% uncertainty on the incoherent deuteron GDH sum (i.e. the contribution above the pion production threshold). The statistical uncertainty is negligible (0.9%). This accuracy is similar to the precision of the GDH verification made at MAMI and ELSA on the proton [16, 24].

The uncertainty on the neutron GDH sum would be 14%, assuming a 10% uncertainty due to the neutron extraction from the deuteron.

5 Total Uncertainty

Table (4) gives the uncertainties on Γ_1^d for different Q^2 points, which we describe here in detail:

- δ_{DIS} : the uncertainty on Γ_1^d due to the unmeasured contribution to the integral from $W = W_{max}$ to $W = \infty$, assuming a 50% accuracy of the model. $W_{max} =$ 2.0 GeV for all points except the first, for which the upper limit is 1.8 GeV.

[‡] The slope predicted by the GDH sum rule, χPT calculations from Ji *et al.* [34], and Bernard *et al.* [88, 89], and the phenomenological models of Soffer and Teryaev [101], and Burkert and Ioffe [100].

Q^2 (GeV^2)	δ_{DIS}	δ_{trans}	$\delta\sigma_{born}$	δ_{syst}^{tot}	δ_{stat}
0.015	1.9	0.5	8.9	9.1	2
0.02	2.2	0.7	8.9	9.2	3
0.05	1.5	1.1	8.9	9.1	8
0.10	1.1	1.7	8.9	9.1	13
0.15	0.2	2.2	8.9	9.2	22
0.20	1.1	2.7	8.9	9.4	30

Table 4: Systematic uncertainty (in percent) on Γ_1^d. For reference we list the expected statistical precision in the final column.

- δ_{trans} : the uncertainty due to the absence of transverse target spin data. This error is discussed in detail in Section 3.3.
- $\delta\sigma_{born}$: the uncertainty on the absolute polarized cross section difference after radiative corrections. This includes the uncertainties on absolute unpolarized cross section, asymmetries, polarized ^{15}N background and radiative corrections.
- δ_{syst}^{tot} : the total systematic uncertainty, added in quadrature.
- δ_{stat} : the statistical uncertainty.

6 Summary

In summary, we propose to measure the extended GDH integral on the neutron and deuteron in the range 0.015<Q^2<0.2 GeV^2. The main goals of this measurement are:

1. To measure for the first time the full generalized GDH sum on the deuteron at low Q^2. This would provide insight into the role the disintegration channel plays in the satisfaction of the deuteron GDH sum rule.
2. To provide a check of χPT and lattice calculations for the deuteron and neutron;
3. To measure the neutron GDH integral extracted from the deuteron, which is a necessary complement to the data already taken on ^{3}He (Hall A experiment E97-110 [2]). The nuclear corrections involved in the extraction of neutron from a polarized nuclear target are increasingly complex and sizable at low Q^2 and must be verified with complementary targets, such as D and ^{3}He;
4. To measure the Bjorken sum at very low Q^2 when combined with proton data from Hall B experiment E03-006 [1]. The similar experimental setup of the two experiments will minimize any relative systematic uncertainty.
5. Additionally, such a measurement would provide a check of the (real photon) GDH sum rule on the deuteron and neutron via extrapolation to $Q^2 = 0$.

The proposed measurement is very similar to the approved proton GDH experiment, E03-006. With 20 days beam time we can reach a statistical uncertainty that is 1.5 times larger than the proton measurement, but with a similar systematic uncertainty. This proposed experiment can optimize the productivity of the JLab physics program by taking advantage of beamtime available immediately after E03-006 that will be otherwise wasted. To improve the accuracy and completeness of our measurement above $Q^2 = 0.04$ GeV^2, would require an additional 10 days of running at a higher energy (eg. 2.6 GeV) as first requested in our previous proposal.

We have also submitted a proposal [86] for a short run in Hall C to this PAC to measure the threshold contribution to the extended GDH sum rule, which would completely eliminate any model dependence of our final results.

A Resolution in the Sub-threshold Region.

The 10 MeV momentum resolution of the CLAS detector will make it difficult to separate the electro-disintegration contribution from the quasi-elastic and elastic contributions. This could be a problem since the elastic contribution should not be included in the GDH sum. However, the elastic contribution is well known, and reasonably accurate calculations [81, 82, 83] exist for the deuteron sub-threshold contributions at low Q^2. With knowledge of the CLAS energy resolution, one can try to disentangle the various contributions by using an iterative technique.

This case is very similar to radiative correction procedures. In radiative corrections, QED is the highly precice 'law' which rules the transformation from a Born cross section to the non-Born cross section measured in the experiment. In a typical radiative correction procedure, a model for the Born cross section is first radiated following the QED laws and is compared to the experimental result. The initial model is then adjusted iteratively until the radiated model matches the data. In our case, the transformation law is also known (a Gaussian convolution) as well as the final spectrum that will be measured, and reasonable models exist for the input.

In the section below, we construct a spectrum which reflects the effect of the experimental resolution. Then, we go through the exercise of deconvoluting it in order to estimate the precision at which we can extract the sub-threshold contribution of the GDH sum.

A.1 Experimental spectrum.

To construct the experimental spectrum, we use Arenhovel's [15] result on σ_{TT} for the electro-disintegration and quasi-elastic contributions. We add an elastic peak at $W = M_d$. This input model is shown[§] in panel (1,3) of Fig. 9 for $Q^2 = 0.04$ GeV^2. We convolute this spectrum with a Gaussian distribution of 10 MeV total width to obtain (2,3). This represents a typical measured spectrum, from which we will try to recover the input distribution.

A.2 Deconvolution

We start with a test model (1,2) with very different shape compared to the input model (1,3), but which is constrained to keep the same structure (i.e. three contributions: elastic, electro-desintegration and quasielastic) and the same well known elastic peak. Compared to the input model, the electro-disintegration contribution has been enhanced, while the quasi-elastic contribution has been suppressed. We convolute the test model with a Gaussian of 9 MeV full width to obtain (2,2). We used a different resolution (9 MeV) compared to the input model (10 MeV) to account for the uncertainty in the CLAS resolution. We note that high statistics data on the elastic proton peak will be obtained in the same experimental conditions by E03-006. As a consequence, we expect to know the resolution accurately.

[§] For ease of discussion, we refer to the 9 individual panels in Fig. 9 by their column and row position. For example, the panel in the far right column of the bottom row is referred to by (3,1).

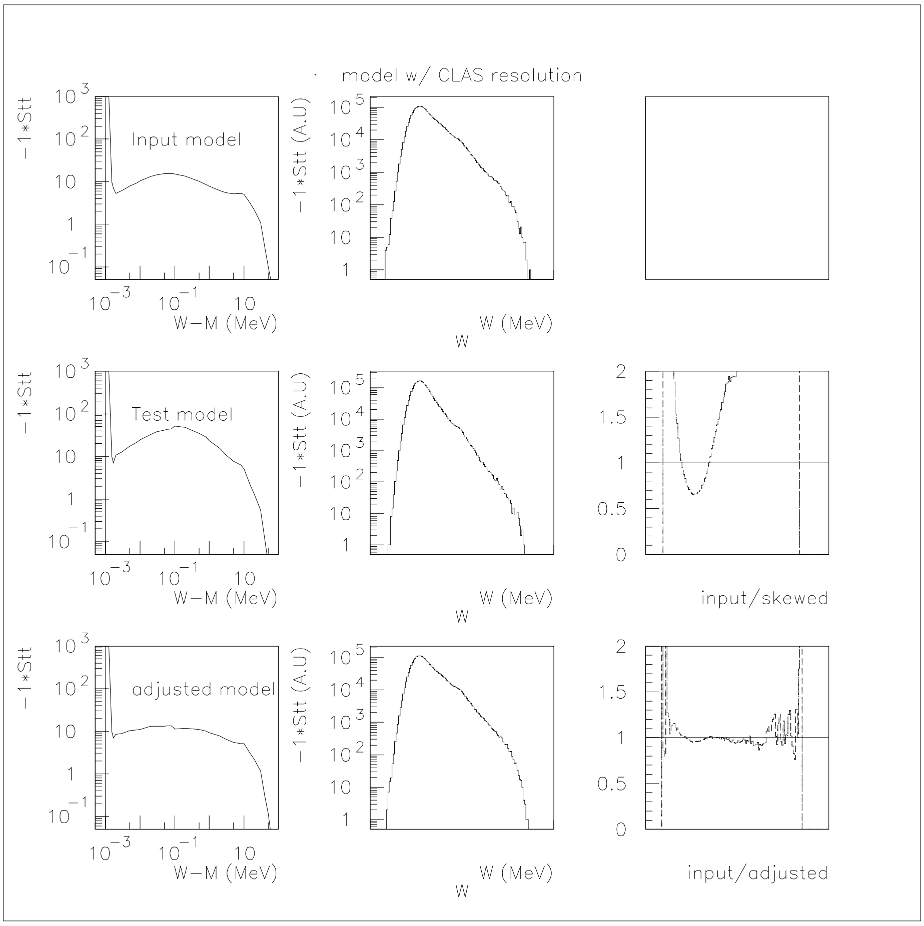

Figure 9: **Top row** Left: input model. Center: input model smeared with experimental resolution. **Middle row** Left: test model. Center: smeared test model Right : ratio of input to test model. **Bottom row** Left: final iterated result. Center: final result smeared with experimental resolution. Right : ratio of input to final model.

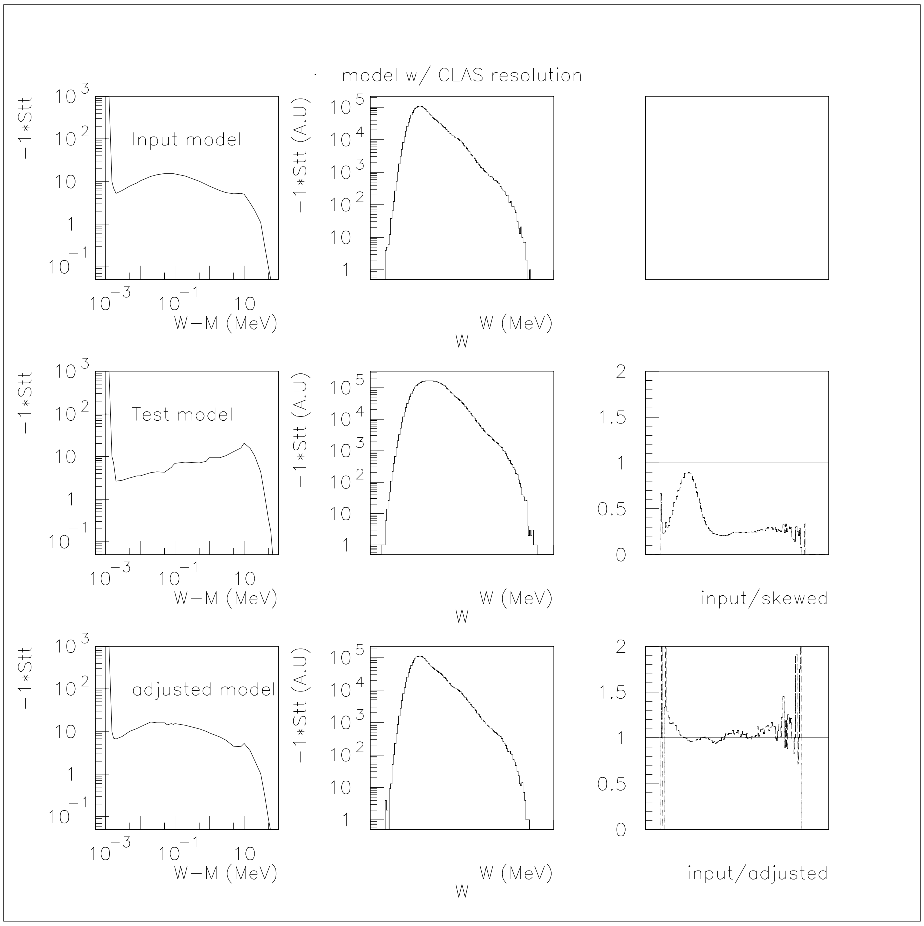

Figure 10: Same as Fig. 9 but with a different starting point for the test model and a test resolution of 11 MeV.

Panel (3,2) shows the ratio of the input model to test model, after their convolution with respectively 10 and 9 MeV width Gaussians. We use this ratio to adjust the test model. After a few iterations, we obtain the adjusted model shown on the bottom row. Panel (1,1) is with infinite resolution, while (2,1) is after convolution with a 9.8 MeV Gaussian. (3,1) is the ratio of (2,1) to (2,3). The adjusted model is satisfactory since this ratio is about unity. To estimate the error on the sub-threshold contribution to the GDH sum, we compute the integrals of (1,3) and (1,1) weighted by $1/\nu$. The elastic contribution is excluded from the integrals. The two numbers matches within 4%.

In Fig. 10, we show another example of deconvolution with, in this case, a test model in which the electro-disintegration channel has been suppressed, the quasi-elastic contribution has been enhanced and an energy resolution of 11 MeV has been used. After iterations, we can recover the sub-threshold contribution to the GDH sum to within 2.5%.

We note that we are applying the deconvolution process to a quantity related to differences of polarized cross sections, for which all unpolarized contributions cancel. Since we do not expect the backgrounds to be polarized[¶], their contributions are suppressed and we disregard them in this exercise.

Given the results above, we expect to recover the sub-threshold contribution to within 10%.

B Extraction of Neutron Quantities from ^{3}He and D.

Neutron information is essential to our understanding of the strong interaction and nucleon structure. Many groups [108] have worked out extraction procedures, although this list of references is not exhaustive. We will focus here mainly on the work of Ciofi Degli Atti and collaborators [4, 3, 109].

In the description below, the limitations of the extraction procedures will be apparent, thus demonstrating the need for experimental results from both D and ^{3}He. Tests against both D and ^{3}He experimental results will be needed to establish the reliability of the more sophisticated procedures that are necessary to extract the neutron.

B.1 ^{3}He

In Experiment E97-110, neutron information has to be extracted from ^{3}He data. The ^{3}He nucleus is not in a pure S state. The admixture of S$'$ and D states can reach about 10%. This makes the protons of the ^{3}He nucleus come into play. In DIS, this can be formalized using the concept of non-zero proton effective polarization $P_p \neq 0$. For the same reason part of the neutron spin is pointing in the opposite direction than the ^{3}He spin (neutron effective polarization $P_n < 1$). Other nuclear corrections accounted for in this extraction procedure come from the Fermi motion and the binding. The correction method for DIS data was first worked out for ^{3}He by Friar et al. [110] and then by Ciofi Degli Atti et al. [109]. The method was then applied to the GDH sum rule by Ciofi Degli Atti and Scopetta [4].

[¶] The prescence of ^{15}N in the ammonia used in the polarized target introduces a small asymmetry [107] which should be negligible.

The proton and neutron effective polarizations within the ^{3}He nucleus are computed either using three-body Fadeev calculations or by integrating elements of the matrix representing the spin dependent spectral function (both methods agree). Without any nuclear effects other than the admixture of the S$'$ and D states, the different spin structure functions would obey the equation:

$$g^{^3He} = 2p_p g^p + p_n g^n \tag{13}$$

with $p_p = -0.028 \pm 0.004$ and $p_n = 0.86 \pm 0.02$ [109].

Assuming that the spin structure functions have the same form for a bound nucleon and a free nucleon, then the Fermi motion and binding effect can be taken into account by integrating the structure functions over a shifted energy transfer, *i.e.*, these effects are accounted for by convoluting g_1 and g_2 with a quantity related to the ^{3}He spectral function [109] calculated in the plane wave impulse approximation (PWIA). This method holds in principle for the quasi-elastic, resonances and DIS domains. Ciofi Degli Atti *et al.* demonstrate that in the DIS region Eq. (13) is already a good approximation and the refinement by the convolution method modifies the result by at most 4% (for $x < 0.8$) [109]. However in the resonance region Eq. (13) is not sufficient for a reliable extraction of the neutron data [4] due to Fermi motion and binding.

Since the generalized GDH integral is an integration over the spin structure function g_1, the method used to extract the spin structure functions on the neutron can also be applied to the generalized GDH integral. A comparison of the extraction of the neutron GDH integral using, on the one hand, only the effective polarizations method (cf Eq. (13)) and, on the other hand the PWIA method, shows that in both cases the GDH integral is similar. Hence, for integrated quantities, in a domain where PWIA is justified, the neutron can be extracted either by simply accounting for effective polarization or by using the convolution method. However, PWIA does not account for nuclear effects such as Final State Interactions and Meson Exchange Currents which are known to be increasingly important at low Q^2. EMC effects are also not included. Furthermore, Pauli blocking is not included in PWIA and it should play an important role at low Q^2, which may explain the striking result of experiment E94010 which shows a large positive trend of the GDH sum on ^{3}He at low Q^2, while the sum rule at the photon point has a large negative value (-498 μbarn) (see Fig. (11)) [111]. The increasing complexity of the extraction at low Q^2 is reflected in the uncertainty of the PWIA which is estimated to range from 5% at large Q^2 to 10% at $Q^2 = 0.1$ GeV^2. This estimate is obtained by comparing the PWIA and effective polarization results and assuming that the difference is representative of the neutron extraction uncertainty. Although accounting for nuclear effects appears to be difficult at low Q^2, there is on-going work to include final state interactions in the PWIA model [112].

B.2 Deuterium

In the DIS limit, a convolution method based on the impulse approximation is also used to extract the neutron from the deuteron [3]. The electron-nucleon scattering amplitude is convoluted with the wave function of the nucleon inside the deuteron.

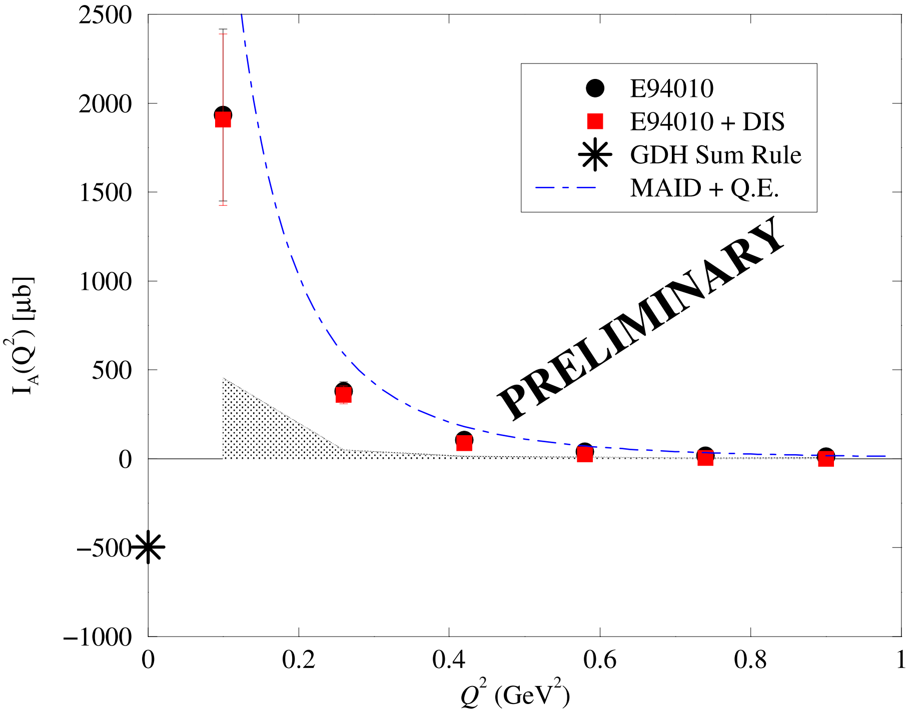

Figure 11: Preliminary results on the generalized GDH sum on ^{3}He.

The most important nuclear effects, for SSF in DIS, are Fermi-motion and the D-Wave depolarization effect. The convolution can be expressed as:

$$g_1^D(x,Q^2) = \int_x^{M_D/m} \frac{dy}{y} g_1^N(x/y,Q^2)\overrightarrow{f_D}(y) \tag{14}$$

where $\overrightarrow{f_D}(y)$ is the “spin dependent effective distribution of the nucleons” and $g_1^N = (g_1^p + g_1^n)/2$. $\overrightarrow{f_D}(x)$ has a sharp maximum at $y \simeq 1.0$ and is normalized to (1-1.5ω_D), leading to the usual approximate formula:

$$g_1^D = \frac{1}{2}(g_1^p + g_1^n)(1 - 1.5\omega_D) \tag{15}$$

with $\omega_D \simeq 0.05$ from N-N potential calculations. Eq. (15) becomes an exact consequence of Eq. (14) if moments are considered.

At finite Q^2 and ν, the integration limit of Eq. (14) and $\overrightarrow{f_D}(y)$ become x-dependent, so in principle Eq. (15) does not hold. In practice, corrections are small (0.3% effect at Q^2=1 GeV^2).

Just like for ^{3}He, the simple Eq. (15) is not reliable in the resonance region due to Fermi smearing, but can be used to a good approximation for moments, as long as Q^2 is not too small. The change in normalization of $\overrightarrow{f_D}(y, x, Q^2)$ with respect to $\overrightarrow{f_D}(y)$ leads to a correction term $N_f(Q^2)$:

$$g_1^D = \frac{1}{2}(g_1^p + g_1^n)(1 - 1.5\omega_D)N_f(Q^2) \tag{16}$$

that can be interpreted as the effective number of nucleons seen by the virtual photon. The correction $N_f(Q^2)$ grows at low Q^2: $N_f(Q^2 \to \infty) = 1$, $N_f(Q^2 = 1) = 0.997$ and $N_f(Q^2 = 0.1) = 1.02$ [3].

As for ^3He, nuclear effects in deuterium, such as final state interactions, that are known to be important at low Q^2 from unpolarized data, are not included in the extraction model. Given the large number of theory groups involved in these topics, deuterium data available at low Q^2 should push the calculations beyond the present approximations.

C Impact of Beamtime Request on Statistical Error

In Figs. (12) and (13), we display the precision for Γ_1 that may be achieved with 30 days as requested in the previous PAC. These figures should be compared to Figs. (6) and (7).

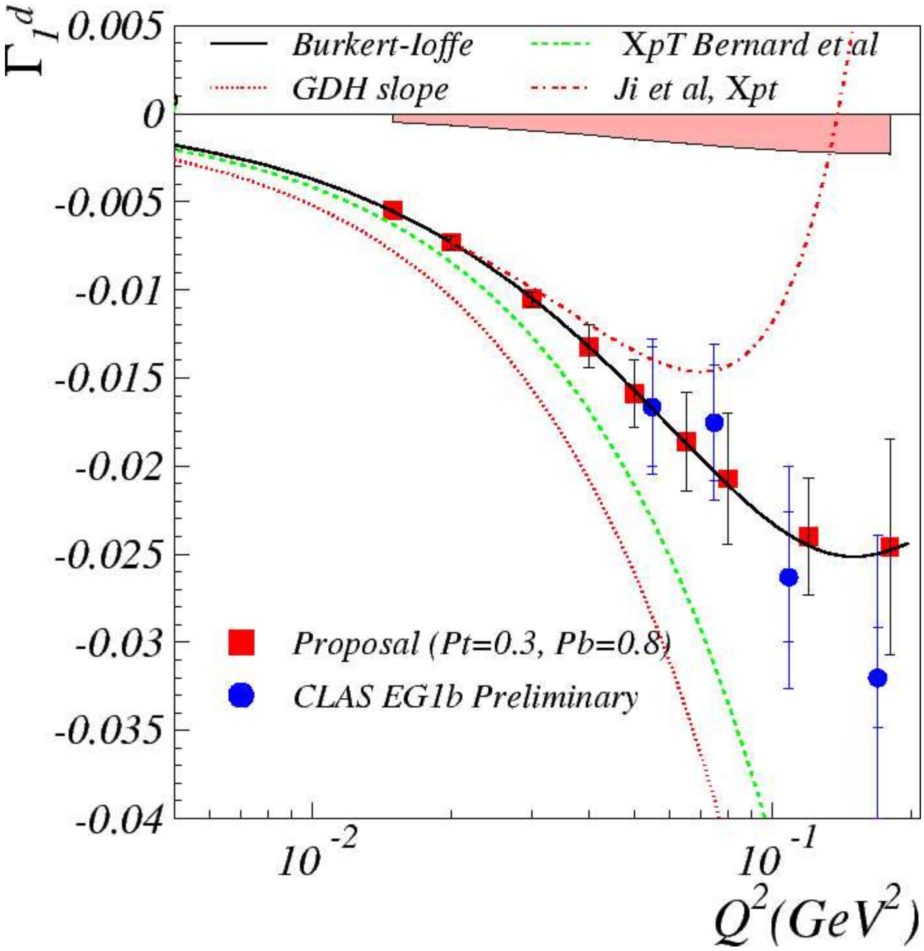

Figure 12: Expected precision of deuteron Γ_1. The band represents the systematic uncertainty, while the error bars on the points are statistical only. The curves from Bernard *et al.* [88, 89] and Ji *et al.* [34] are χPT calculations. The curve from Burkert-Ioffe [100] and Soffer-Teryaev [101] are phenomenological models. The preliminary EG1B data [42] are shown for comparison.

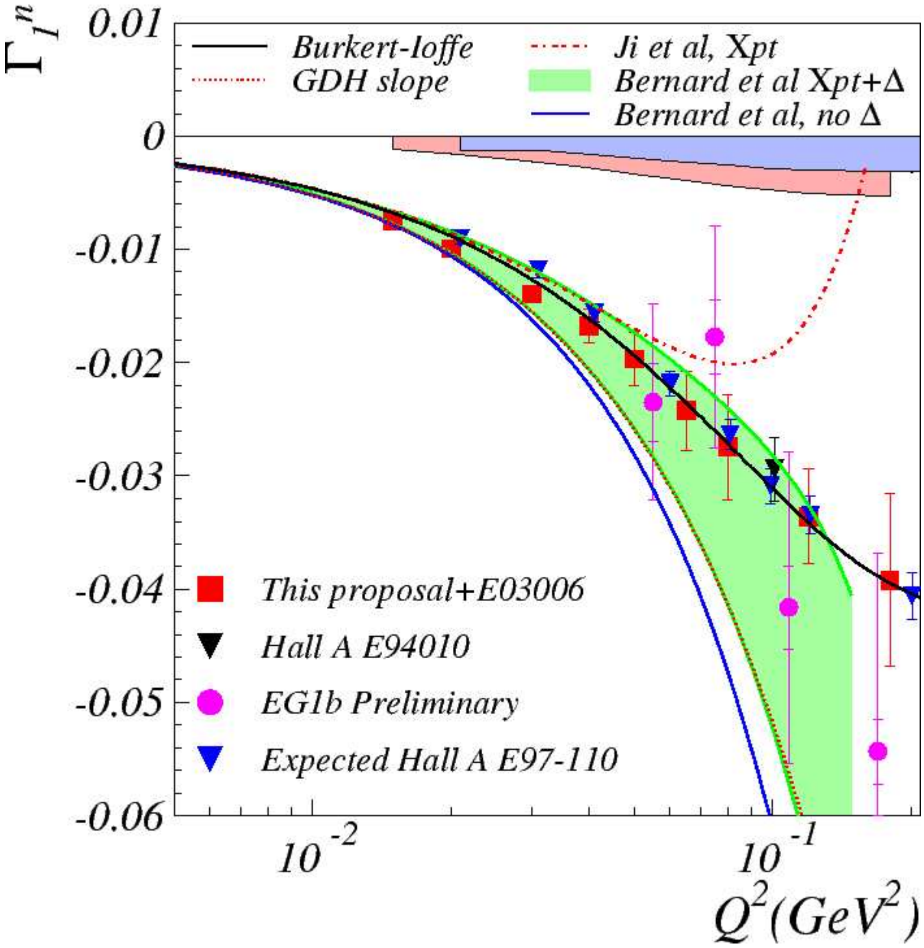

Figure 13: Expected precision of neutron Γ_1. The error bar contains both statistical and systematic uncertainty. We assume 20% uncertainty from the neutron extraction from both ^{3}He and the deuteron. The projected uncertainties for the present proposal include the error on the proton measurement. The relevant domain for comparing neutron extracting from ^{3}He and D is below $Q^2 \sim 0.1$, where the known method to extract the neutron becomes less reliable. The points at higher Q^2 are ancillary results coming from the higher beam energy runs necessary to expand the W coverage of the lower Q^2 points. See Fig. (6) for a description of theoretical curves.

References

[1] *JLab E03-006*, M. Ripani, M. Battaglieri, A. Deur and R. deVita spokespersons.

[2] *JLab E97-110*, J.P. Chen , A. Deur, and F. Garibaldi spokespersons.

[3] C. Ciofi degli Atti, L. P. Kaptari, S. Scopetta, and A. Y. Umnikov, Phys. Lett. **B376**, 309 (1996).

[4] C. Ciofi degli Atti and S. Scopetta, Phys. Lett. **B404**, 223 (1997).

[5] U.-G. Meiβner, private communication.

[6] E. Epelbaum, W. Glockle, and U.-G. Meissner, Nucl. Phys. **A747**, 362 (2005).

[7] S. R. Beane *et al.*, Nucl. Phys. **A747**, 311 (2005).

[8] M. J. Savage, PoS **LAT2005**, 020 (2005).

[9] V. Burkert, private communication.

[10] F. E. Low, Phys. Rev. **96**, 1428 (1954).

[11] M. Gell-Mann and M. L. Goldberger, Phys. Rev. **96**, 1433 (1954).

[12] M. Gell-Mann, M. L. Goldberger, and W. E. Thirring, Phys. Rev. **95**, 1612 (1954).

[13] S. Gerasimov, Sov. J. Nucl. Phys. **2**, 430 (1966); S. D. Drell and A. C. Hearn, Phys. Rev. Lett. **16**, 908 (1966); M. Hosoda and K. Yamamoto, Prog. Theor. Phys. **30**, 425 (1966).

[14] S. D. Bass, Z. Phys. **A355**, 77 (1996).

[15] H. Arenhoevel, Phys. Lett. **B595**, 223 (2004).

[16] J. Ahrens *et al.*, Phys. Rev. Lett. **87**, 22003 (2001).

[17] J. Ahrens *et al.*, Phys. Lett. **B551**, 49 (2003).

[18] H. Dutz *et al.*, Phys. Rev. Lett. **91**, 192001 (2003).

[19] H. Dutz *et al.*, Phys. Rev. Lett. **93**, 032003 (2004).

[20] *JLab E04-102*, D. Crabb, M. Khandaker, and D. Sober spokespersons.

[21] *SLAC proposal E-159*, P.E. Bosted and D. Crabb spokespersons.

[22] H. Dutz *et al.*, Phys. Rev. Lett. **94**, 162001 (2005).

[23] O. Jahn, in *Proceedings of the 3rd International Symposium on the GDH Sum Rule and its extensions*, 1st ed., edited by S. Kuhn and J.P. Chen (World Scientific, New Jersey, 2005).

[24] K. Helbing, in *Proceedings of the 3rd International Symposium on the GDH Sum Rule and its extensions*, 1st ed., edited by S. Kuhn and J.P. Chen (World Scientific, New Jersey, 2005).

[25] R. A. Arndt, W. J. Briscoe, I. I. Strakovsky, and R. L. Workman, (2005).

[26] R. A. Arndt, W. J. Briscoe, I. I. Strakovsky, and R. L. Workman, Phys. Rev. **C66**, 055213 (2002).

[27] H. R. Weller, in *Proceedings of the 3rd International Symposium on the GDH Sum Rule and its extensions*, 1st ed., edited by S. Kuhn and J.P. Chen (World Scientific, New Jersey, 2005).

[28] H. R. Weller, in *Proceedings of the Second International Symposium on the GDH Sum Rule and the Spin Structure of the Nucleon*, 1st ed., edited by M. Anghinolfi, M. Battaglieri, and R. D. Vita (World Scientific, New Jersey, 2003).

[29] C. S. Whisnant *et al.*, in *Proceedings of the 3rd International Symposium on the GDH Sum Rule and its extensions*, 1st ed., edited by S. Kuhn and J.P. Chen (World Scientific, New Jersey, 2005).

[30] http://www.legs.bnl.gov/.

[31] M. Anselmino, B. L. Ioffe, and E. Leader, Sov. J. Nucl. Phys. **49**, 136 (1989).

[32] J. D. Bjorken, Phys. Rev. **148**, 1467 (1966).

[33] D. Drechsel, S. S. Kamalov, and L. Tiator, Phys. Rev. **D63**, 114010 (2001).

[34] X.-D. Ji and J. Osborne, J. Phys. **G27**, 127 (2001).

[35] B. Adeva *et al.*, Phys. Rev. **D58**, 112001 (1998).

[36] K. Abe *et al.*, Phys. Rev. Lett. **78**, 815 (1997).

[37] K. Ackerstaff *et al.*, Phys. Lett. **B444**, 531 (1998).

[38] M. Amarian *et al.*, Phys. Rev. Lett. **89**, 242301 (2002).

[39] K. Slifer *et al.*, (E94010 collaboration) in preparation.

[40] R. Fatemi *et al.*, Phys. Rev. Lett. **91**, 222002 (2003).

[41] J. Yun *et al.*, Phys. Rev. **C67**, 055204 (2003).

[42] G. Dodge, in *Proceedings of the 3rd International Symposium on the GDH Sum Rule and its extensions*, 1st ed., edited by S. Kuhn and J.P. Chen (World Scientific, New Jersey, 2005).

[43] K. Abe *et al.*, Phys. Rev. **D58**, 112003 (1998).

[44] P. L. Anthony *et al.*, Phys. Lett. **B493**, 19 (2000).

[45] A. Airapetian *et al.*, Eur. Phys. J. **C26**, 527 (2003).

[46] *JLab E03-109*, S. Choi, Z.-E. Meziani and O. Rondon spokespersons.

[47] P. L. Anthony *et al.*, Phys. Rev. **D54**, 6620 (1996).

[48] K. Abe *et al.*, Phys. Rev. Lett. **79**, 26 (1997).

[49] X. Zheng *et al.*, Phys. Rev. **C70**, 065207 (2004).

[50] *JLab E01-012*, N. Liyanage, J-P. Chen, and Seonho Choi spokespersons.

[51] K. Abe *et al.*, Phys. Lett. **B404**, 377 (1997).

[52] *JLab E01-006*, O. Rondon and M. Jones spokespersons.

[53] K. Kramer *et al.*, Phys. Rev. Lett. **95**, 142002 (2005).

[54] W. Bartel *et al.*, Nucl. Phys. **B58**, 429 (1973).

[55] A. Lung *et al.*, Phys. Rev. Lett. **68** 3841 (1992); P. Bosted *et al.*, Phys. Rev. Lett. **70** 718 (1993).

[56] P. Markowitz *et al.*, Phys. Rev. **C48**, 5 (1993).

[57] H. Anklin *et al.*, Phys. Lett. **B336**, 313 (1994).

[58] E. E. W. Bruins *et al.*, Phys. Rev. Lett. **75**, 21 (1995).

[59] H. Anklin *et al.*, Phys. Lett. **B428**, 248 (1998).

[60] G. Kubon *et al.*, Phys. Lett. **B524**, 26 (2002).

[61] *JLab E94-017*, W. K. Brooks and M. F. Vineyard, see e.g. nucl-ex/0504028.

[62] H. Gao *et al.*, Phys. Rev. **C50**, 546 (1994).

[63] W. Xu *et al.*, Phys. Rev. Lett. **85**, 2900 (2000).

[64] W. Xu *et al.*, Phys. Rev. **C67**, 012201 (2003).

[65] S. Galster *et al.*, Nucl. Phys. **B32**, 221 (1971).

[66] S. Platchkov *et al.*, Nucl. Phys. **A510**, 740 (1990).

[67] T. Eden *et al.*, Phys. Rev. **C50**, 1749 (1994).

[68] C. Herberg *et al.*, Eur. Phys. J. **A5**, 131 (1999).

[69] I. Passchier *et al.*, Phys. Rev. Lett. **82**, 4988 (1999).

[70] M. Ostrick *et al.*, Phys. Rev. Lett. **83**, 276 (1999).

[71] R. Schiavilla and I. Sick, Phys. Rev. **C64**, 041002 (2001).

[72] H. Zhu *et al.*, Phys. Rev. Lett. **87**, 081801 (2001).

[73] R. Madey *et al.*, Phys. Rev. Lett. **91**, 122002 (2003).

[74] D. I. Glazier *et al.*, Eur. Phys. J. **A24**, 101 (2005).

[75] *JLab E04-110*, R. Madey *et al.* spokespersons.

[76] M. Meyerhoff *et al.*, Phys. Lett. **B327**, 201 (1994).

[77] J. Bermuth *et al.*, Phys. Lett. **B564**, 199 (2003).

[78] *JLab E02-013*, B. Wojtsekhowski *et al.* spokespersons.

[79] H. Arenhovel, A. Fix, and M. Schwamb, in *Proceedings of the 3rd International Symposium on the GDH Sum Rule and its extensions*, 1st ed., edited by S. Kuhn and J.P. Chen (World Scientific, New Jersey, 2005), nucl-th/0409015.

[80] H. Arenhovel, A. Fix, and M. Schwamb, Phys. Rev. Lett. **93**, 202301 (2004).

[81] H. Arenhovel, private communication.

[82] H. Arenhovel, W. Leidemann, and E. L. Tomusiak, Eur. Phys. J. **A23**, 147 (2005).

[83] W. Leidemann, E. L. Tomusiak, and H. Arenhovel, Phys. Rev. **C43**, 1022 (1991).

[84] R. G. Arnold *et al.*, Phys. Rev. **C42**, 1 (1990).

[85] M. Frodyma *et al.*, Phys. Rev. **C47**, 1599 (1993).

[86] Proposal to PAC 29 (2005), *Threshold contribution to the Deuteron Extended GDH Sum Rule*, K. Slifer, A. Deur, *et al.*

[87] M. Amarian *et al.*, Phys. Rev. Lett. **93**, 152301 (2004).

[88] V. Bernard, N. Kaiser, and U. G. Meissner, Phys. Rev. **D48**, 3062 (1993).

[89] V. Bernard, T. R. Hemmert, and U.-G. Meissner, Phys. Lett. **B545**, 105 (2002).

[90] X. Ji, J. Osborne. J. Phys. G27, 127 (2001) ; X. Ji, C-W Kao, J. Osborne. Phys. Rev. D61 074003 (2000).

[91] I. Karliner, Phys. Rev. **D7**, 2717 (1973).

[92] R. L. Workman and R. A. Arndt, Phys. Rev. **D45**, 1789 (1992).

[93] S. A. Kulagin, W. Melnitchouk, G. Piller, and W. Weise, Phys. Rev. **C52**, 932 (1995).

[94] *2003 Hall A Status report*, p58, http://hallaweb.jlab.org/publications/StatusReports/StatusReport2003.ps.

[95] V. D. Burkert, Phys. Rev. **D63**, 097904 (2001).

[96] A. Deur *et al.*, Phys. Rev. Lett. **93**, 212001 (2004).

[97] C. D. Keith *et al.*, Nucl. Instrum. Meth. **A501**, 327 (2003).

[98] S. Kuhn, Hall B model, private communication.

[99] V. Dharmawardane, private communication.

[100] V. D. Burkert and B. L. Ioffe, Phys. Lett. **B296**, 223 (1992).

[101] J. Soffer and O. V. Teryaev, Phys. Lett. **B545**, 323 (2002).

[102] B. A. Mecking *et al.*, Nucl. Instrum. Meth. **A503**, 513 (2003).

[103] L. W. Mo and Y.-S. Tsai, Rev. Mod. Phys. **41**, 205 (1969).

[104] I. V. Akushevich and N. M. Shumeiko, J. Phys. **G20**, 513 (1994).

[105] M. Amarian *et al.*, Phys. Rev. Lett. **92**, 022301 (2004).

[106] E. Thomas and N. Bianchi, Nucl. Phys. Proc. Suppl. **82**, 256 (2000).

[107] M. Jones, *The* ^{15}N *correction to the measured asymmetries*, RSS technical note 2005-01 (2005).

[108] J. Friar et al. Phys. Rev. **C42**. 2310.(1990); I.R. Afnan *et al*. Phys. Lett. **B493** 36 (2000); Phys. Rev.**C68** 035201 (2003); G.Piller, W.Melnitchouk, A.W.Thomas Phys. Rev. **C54** 894 (1996); M. Lacombe *et al*, Phys. Rev. **C21** 861 (1980); M. J. Zuilhof and J. A. Tjon Phys, Rev. **C22** 2369 (1980); K. Kotthoff, R. Machleidt and D. Schutte, Nucl. Phys. **A264** 484 (1976); B. Desplanques, Phys. Lett. **B203** 200 (1988); L.P. Kaptari and A.Yu. Umnikov, Phys. Lett. **B240** 203 (1990); L.P. Kaptari, A.Yu. Umnikov, C. Ciofi degli Atti, S. Scopetta, and K.Yu. Kazakov, Perugia Report No. DFUPG 92/94 (1994); L.L. Frankfurt and M.I. Strikman, Nucl. Phys. **A405** 557 (1983); R.M. Woloshyn, Nucl. Phys. **A496** 749 (1989); L.P. Kaptari, K.Yu. Kazakov, A.Yu. Umnikov and B. KÃd'mpfer, Phys. Lett. **B321** 271 (1994); M.V. Tokarev, Phys. Lett. **B318** 559 (1993); W. Melnitchouk, G. Piller and A.W. Thomas, Phys. Lett. **B346** 165 (1995); A.Yu. Umnikov, L.P. Kaptari, K.Yu. Kazakov, and F.C. Khanna, Alberta Report No. Thy 29 94 (1994).

[109] C. Ciofi degli Atti, S. Scopetta, E. Pace, and G. Salme, Phys. Rev. **C48**, 968 (1993).

[110] J. L. Friar *et al.*, Phys. Rev. **C42**, 2310 (1990).

[111] K. Slifer, in *Proceedings of the* 3^{rd} *International Symposium on the GDH Sum Rule and its extensions*, 1st ed., edited by S. Kuhn and J.P. Chen (World Scientific, New Jersey, 2005).

[112] A. Kievsky, E. Pace, and G. Salme, (2005), nucl-th/0501060.