Measurement of the $^{3}\text{He}$ spin-structure functions and of neutron ($^{3}\text{He}$) spin-dependent sum rules at $0.035 \leq Q^{2} \leq 0.24$ GeV$^{2}$

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The study of nucleon spin structure has been actively pursued over the past thirty years [1], both theoretically and experimentally at several laboratories, including CERN [2], SLAC [3,4], DESY [5,6] and Jefferson Lab (JLab) [7–15] using doubly polarized inclusive lepton scattering. This research provides a powerful means to study the strong force and its gauge theory, quantum chromodynamics (QCD). They are well tested at high momenta where perturbative expansions in $\alpha_s$, QCD’s coupling, are feasible. Extensive data also exist at intermediate momenta. Yet, at the low momenta characterizing the domain of quark confinement, there are no precision data. There, studies are complicated by 1) the difficulty of finding calculable observables, and 2) the inapplicability of perturbative QCD due to the steep increase of $\alpha_s$ [16]. Sum rules offer a remarkable opportunity to address the first problem by equating measurable moments of structure functions to calculable Compton scattering amplitudes. The second challenge demands the use of non-perturbative techniques such as lattice QCD, or of effective approaches such as chiral effective field theory ($\chi$EFT) [17]. In $\chi$EFT, the effective hadronic degrees of freedom, relevant at low momenta, are used – rather than the fundamental ones (partons) explicit only at large momenta– and the $\chi$EFT Lagrangian structure is established by the symmetries of QCD.

A spin-dependent sum rule of great interest is the one of Gerasimov, Drell, and Hearn (GDH) [18]. It links an integral over the excitation spectrum of the helicity-dependent photoabsorption cross-sections to the target’s anomalous magnetic moment $\kappa$. The sum rule stems from causality, unitarity, and Lorentz and gauge invariances. Its expression for a spin-$1/2$ target is:

$$\int_{v_0}^{\infty} \left( \sigma_{1/2}(v) - \sigma_{3/2}(v) \right) \frac{dv}{v} = \frac{2\pi^2}{M_t^2} \kappa^2,$$

where $M_t$ is the target mass, $v$ the photon energy, $v_0$ the inelastic threshold and $\kappa$ is the fine-structure constant. The $1/2$ ($3/2$) indicates that the photon helicity is parallel (anti-parallel) to the target spin. The GDH sum rule can be applied to various polarized targets such as $^3$He and the neutron, with predictions of $-498.0$ and $-232.5\ \mu b$, respectively. The sum rule was verified on the proton by the MAMI, ELSA, and LEGS experiments [19] with circularly polarized photons of up to $v \approx 3\ \text{GeV}$.

The spin-structure functions $g_1$ and $g_2$, and the spin-dependent partial cross-section $\sigma_{\text{TT}}$ have been extracted from the polarized cross-sections differences, $\Delta \sigma_{1/2}(v, Q^2)$ and $\Delta \sigma_{3/2}(v, Q^2)$ measured for the $^3$He($e, e'X$) reaction, in the E97-110 experiment at Jefferson Lab. Polarized electrons with energies from 1.147 to 4.404 GeV were scattered at angles of $6^\circ$ and $9^\circ$ from a longitudinally or transversely polarized $^3$He target. The data cover the kinematic regions of the quasi-elastic, resonance production and beyond. From the extracted spin-structure functions, the first moments $\Gamma_1(Q^2)$, $\Gamma_2(Q^2)$ and $\Gamma_{\text{TT}}(Q^2)$ are evaluated with high precision for the neutron in the $Q^2$ range from 0.035 to 0.24 GeV$^2$. The comparison of the data and the chiral effective field theory predictions reveals the importance of proper treatment of the $\Delta$ degree of freedom for spin observables.

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Starting in the 1980’s, generalizations of the integrand for virtual photon absorption were proposed [20–22], e.g.:

$$\Gamma_{\text{TT}}(Q^2) \equiv \frac{M_t^2}{8\pi^2 \alpha} \int_{v_0}^{\infty} \frac{\kappa_f(v, Q^2) \sigma_{1/2}(v, Q^2) - \sigma_{3/2}(v, Q^2)}{v} dv = \frac{2M_t^2}{Q^2} \int_0^{x_0} \left[ g_1(x, Q^2) - \frac{4M_t^2}{Q^2} x^2 g_2(x, Q^2) \right] dx,$$

for $\kappa_f = \kappa_f(v, Q^2)$. Different choices of convention have lead to different generalization of the GDH sum [22]. However, the value of $I_{\text{TT}}(Q^2)$ is independent of the choice of $\kappa_f$ since it also normalizes the spin-dependent structure functions, $g_1$ and $g_2$. These relations extend the integrand to $Q^2 > 0$. The sum rule itself was generalized by Ji and Osborne [24] using a dispersion relation involving the forward virtual Compton scattering amplitude $S_{11}(v, Q^2)$ in the $v \to 0$ limit:

$$\Gamma_{\text{TT}}(Q^2) \equiv \int_0^{x_0} g_1(x, Q^2) dx = \frac{Q^2}{8} S_{11}(0, Q^2),$$

where the bar indicates exclusion of the elastic contribution. This relation, valid at any $Q^2$, can be applied back to Eq. (2) equating the moment $\Gamma_{\text{TT}}(Q^2)$ to $A_{\text{TT}}(v, Q^2)$, the spin-flip double virtual Compton scattering amplitude in the $v \to 0$ limit. The amplitudes $S_{11}(0, Q^2)$ and $A_{\text{TT}}(0, Q^2)$ are calculable, e.g. in QCD as four-point functions using lattice techniques [25], or by $\chi$EFT, Eqs. (2) or (3) can then be used to compare these calculations to experimental data. Such data became available at intermediate [7–12] and large $Q^2$ [6] in the 1990s and 2000s. Their lowest $Q^2$ points revealed tensions with the available $\chi$EFT calculations of $S_{11}(0, Q^2)$ and $A_{\text{TT}}(0, Q^2)$ [26,27]. The discrepancies between data and calculations can be due to the $Q^2$ coverage of the experiments being.
not low enough for a valid comparison with χEFT, and/or to the calculations themselves. The data [9–11] showed the importance for χEFT calculations to account for the first excited state (the Δ(1232)) beyond the nucleon ground state. The data also revealed the need for measuring spin moments at Q2 low enough so that χEFT calculations can be accurately tested.

The other spin structure function g2 is expected to obey the Burkhart–Cosmann (BC) sum rule [28]:

$$\Gamma_2(Q^2) = \frac{1}{g_2(x, Q^2)dx} = 0,$$

a super-convergence relation, i.e. implicitly independent of Q2, derived from the dispersion relation for the Compton scattering amplitude S2 (Q2) [21]. The BC sum rule’s validity depends on the convergence of the integral and assumes that g2 is well-behaved as x → 0 [29].

We present here data on g1, g2 and σT⊥ = (σi⊥ − σj⊥)/2 on 3He, and of Γ1, Γ2 and T1 for the neutron, for 0.035 ≤ Q2 ≤ 0.24 GeV2 from experiment E97-110 [30,31]. Data were acquired in Hall A [32] at JLab. We measured the inclusive reaction 3He( e, e’p) with a longitudinally polarized electron beam scattered from longitudinally or transversely (in-plane) polarized 3He [32]. Eight beam energies E and two scattering angles θ were used to cover kinematics at constant Q2, see Fig. 1. The data cover invariant mass W = √M² + 2Mv − Q² (M is the nucleon mass) values from the elastic up to 2.5 GeV; however, only the results above the pion production threshold (W = 1.073 GeV) are discussed here. Spin asymmetries and absolute cross-sections were both measured. The beam polarization was flipped pseudo-randomly at 30 Hz and Møller and Compton polarimeters [32] measured it to average at 75.0 ± 2.3%. The beam current ranged from 1 to 10 μA depending on the trigger rate. The data acquisition rate was limited to 4 kHz to keep the deadtime below 20%.

The 3He target was polarized by spin-exchange optical pumping (SEOP) [33]. Two sets of Helmholtz coils providing a parallel or transverse 2.5 mT uniform field allowed us to orient the 3He spins longitudinally or perpendicularly to the beam direction. The target had about 12 atm of 3He gas in a glass cell consisting of two connected chambers. The SEOP process occurred in the upper chamber, which was illuminated with 90 W of laser light at a wavelength of 795 nm. The electron beam passed through a lower chamber made of a 40 cm-long cylinder with a diameter of 2 cm and hemispherical glass windows at both ends. Two independent polarimeters monitored the 3He polarization: nuclear magnetic resonance (NMR) and electron paramagnetic resonance (EPR). The NMR system was calibrated using adiabatic fast passage and the known thermal equilibrium polarization of water. The polarization was independently cross-checked by measuring the elastic 3He asymmetry. The average in-beam target polarization was (39.0 ± 1.6)%.

The scattered electrons were detected by a High Resolution Spectrometer (HRS) [32] with a lowest scattering angle reachable of 12.5°. A horizontally-bending dipole magnet [34] was placed in front of the HRS so that electrons with scattering angles of 6° or 9° could be detected. The HRS detector package consisted of a pair of drift chambers for tracking, a pair of scintillator planes for triggering and a gas Cherenkov counter, together with a two layer electromagnetic calorimeter for particle identification. Details of the experimental set-up and its performance can be found in [30,31].

The g1 and g2 spin structure functions were extracted from the cross-section differences ∆σI ≡ dσI/daE − dσI/daE′ and ∆σL ≡ dσL/daE − dσL/daE′ for the case where the target polarization is aligned parallel or perpendicular, respectively, to the beam direction:

\[
g_1 = \frac{M Q^2 V}{4 \alpha^2} \frac{1}{E + E'} \left[ \Delta \sigma I + \tan \left( \frac{\theta}{2} \right) \Delta \sigma L \right],
\]

\[
g_2 = \frac{M Q^2 V}{8 \alpha^2 E (E + E')} \left[ -\Delta \sigma I + E + E' \cos \theta \right] \frac{1}{E' \sin \theta} \Delta \sigma L.
\]

The cross-section differences ∆σI, ∆σL were formed by combining longitudinal and transverse asymmetries A1 and A⊥ with the unpolarized absolute cross-section σ0: ∆σI,⊥ = 2σ0A1,⊥. Unpolarized backgrounds cancel in ∆σ and polarized background are negligible since only 3He nuclei are significantly polarized. The asymmetries were corrected for the beam and target polarizations, as well as beam charge and data acquisition lifetime asymmetries. The dilution of the asymmetry by unpolarized background canceling that same background in σ0, such correction is unnecessary when forming ∆σ.

The absolute cross-section was obtained by correcting for the finite HRS acceptance and detector inefficiencies. The 1/ν weighting of the GDH sum emphasizes low ν contributions. Thus, contamination from elastic and quasi-elastic events appearing beyond the electroproduction threshold due to detector resolution and radiative tails was carefully studied and corrected on both σ0 and ∆σI,⊥. The high HRS momentum resolution helped to minimize the contamination. For the neutron moments, the quasi-elastic contamination was studied and subtracted by building a model of our data with guidance from state-of-the-art Faddeev calculations [35] and the MAID [36] model. The estimated uncertainty from the subtraction and the effect of varying the lower limit of integration (to account for below-threshold pion production) were included in our systematic uncertainty. Since g1 and g2 are defined in the Born approximation, radiative corrections were applied following Ref. [37] for the unpolarized case and using Ref. [38] to include polarized effects. In the unfolding procedure described in [36], cross-section model or data at lower energy are required. To avoid a model-dependent systematic uncertainty, lower energy data gathered for that purpose during the experiment were used in the unfolding procedure.

The results for g1 and g2, and for σT⊥ on 3He are shown in Fig. 1 and Fig. 2, respectively. The data are provided from the pion
threshold. The error bars represent the statistical uncertainty. Systematic uncertainties are shown by the lower band for $g_1$ and $\sigma_{\text{TT}}$ or the upper band for $g_2$. The main systematic uncertainties are from the absolute cross-sections (3.5% to 4.5%), beam polarization (3.5%), target polarization (3 to 5%) and radiative corrections (3 to 7%). When combining uncertainties, the uncorrelated ones are added in quadrature. The correlated ones are added linearly. The full systematic uncertainty, shown by the band in Figs. 1 and 2, is the uncorrelated and correlated uncertainties added quadratically. The total systematic for $g_1$ varies between 12% at low $W$ to 9% at high $W$, for $g_2$ it is about 13% over the whole $W$ range, and for $\sigma_{\text{TT}}$ between 11% at low $W$ to 8% at high $W$.

The data display a prominent feature in the $\Delta(1232)$ region. There, $g_1 \approx -g_2$. This is expected, since the $\Delta$ is an M1 resonance for which the longitudinal-transverse interference cross-section $\sigma_{\text{LT}} \propto (g_1 + g_2)$ is anticipated to be highly suppressed [22]. Above the $\Delta$, both spin structure functions decrease in magnitude, to increase again as $W$ approaches 2 GeV while still displaying an approximate symmetry indicating the smallness of $\sigma_{\text{LT}}$.

To obtain $\Gamma_{\text{LT}}^0$ and $p_{\text{LT}}$, we evaluated $g_1$, $g_2$ and $\sigma_{\text{TT}}$ at constant $Q^2$ by interpolating the fixed $\theta$ and $E$ data. The moments were then formed for each value of $Q^2$ with integration limits from pion threshold to the lowest $x$ value experimentally covered, see tables of the Supplemental Material. The same neutron parameterization as used in Ref. [15] was used to complete the integration down to $x = 0.001$, and the recent Regge parameterization [40] was used for $x < 0.001$. The unmeasured part is about 10% of the moments. The parameters of the extrapolation models were varied within their estimated ranges, and the variations were combined into the extrapolation uncertainty.

The neutron moments were obtained using the prescription in Ref. [39] which treats the polarized $^3$He nucleus as an effectively polarized neutron. The resulting uncertainty is 6 to 14%, the higher uncertainties corresponding to our lowest $Q^2$ values. Results for the integrals are given in the tables of the Supplemental Material.

In Fig. 3 our $\Gamma_{\text{LT}}^0$ is compared to $\chi$EFT calculations [27,41,42], models [43,44], the MAID phenomenological parameterization [36] which contains only resonance contributions, and earlier data [7, 10]. Where the $Q^2$ coverages overlap, our data agree with the earlier data extracted either from the deuteron or $^3$He. Our precision is much improved compared to the EG1 data [7] and similar to that of the E94-010 [10] data at larger $Q^2$.

Two $\chi$EFT calculations have become available recently [41,42], improving on the earlier ones [26,27]. Those had used different approaches, and different ways to treat for the $\Delta(1232)$ degree of freedom, a critical component of $\chi$EFT calculations for baryons. For comparison, we also show in Fig. 3 the older calculation [27] in which the $\Delta(1232)$ is not accounted for. The two state-of-art calculations [41,42] account explicitly for the $\Delta$ by computing the $\pi-\Delta$ graphs, but differ in their expansion methods for these corrections and thus on how fast their calculations converge. Comparing them to our data will help to validate the $\chi$EFT approach and determine the most efficient calculation technique. Our $\Gamma_{\text{LT}}^0$ data agree with both calculations up to $Q^2 \approx 0.06$ GeV$^2$, although a $\sim 1.5\sigma$ offset exists between the calculation [42] and the data. They then agree only with calculation [42], which predicts the plateauing of the data. The deviation for $Q^2 \gtrsim 0.06$ GeV$^2$ between data and the calculation from Ref. [41] is expected since, as pointed out in [41], a similar deviation is seen with proton data but not for the isovector quantity $\Gamma_{\text{LT}}^{1(p-n)}$ [12]. The issue thus affects isoscalar combinations and can be traced to the later onset of loop contributions for isoscalar quantities (3 pions, with 2 pions threshold to isoscalar quantities) [41].

$\Gamma_{\text{LT}}^0(Q^2)$ is shown in Fig. 4. The integration using only our data, and that with an estimate of the unmeasured low-$x$ part are represented by the open and solid circles, respectively. The open circles should be compared to the MAID result (solid line), which is larger than the data. Our data and the earlier E94-010 data [9] are consistent. As $Q^2$ decreases, our results drop to around $-325$ nb, agreeing with the $\chi$EFT calculation from Bernard et al. [41] and the earlier one from Ji et al. [27]. The calculation from Lensky et al. [42] displays the same $Q^2$-dependence as the data but with a systematic shift. Extrapolating the data to $Q^2 = 0$ to check the original GDH sum rule is difficult since the calculations that could be used to guide the extrapolation markedly disagree. Data at lower $Q^2$ or a theoretical consensus on the $Q^2$-dependence of $\Gamma_{\text{LT}}^0$ are needed to address the validity of the original GDH sum rule on the neutron.

$\Gamma_{\text{LT}}^0(Q^2)$ is shown in Fig. 5. The stars show the measured integral without low-$x$ extrapolation for the neutron, to be compared with MAID. This model underestimates the higher $Q^2$ data
Fig. 4. $\Gamma_{0}(Q^{2})$ with (filled circles) and without (open circles) the estimated unmeasured low-$x$ contribution. The meaning of the inner and outer error bars and of the band is the same as in Fig. 3. Also shown are $\chi$ EFT results, MAID (solid line) and earlier E94-010 data [9].

But agrees well at lower $Q^2$. The open circles represent the integral including an estimate for the low-$x$ contribution assuming $g_2 = g_2^{WW}$ [4], where $g_2^{WW}$ is the twist-2 part of $g_2$ [45]. This procedure is used since there are little data to constrain $g_2$ at low-$x$. Since it is unknown how well $g_2^{WW}$ matches $g_2$ there, one cannot reliably assess an uncertainty on the low-$x$ extrapolation and none was assigned. The solid circles show the full integral with the elastic contribution evaluated using Ref. [46]. These data allow us to investigate the BC sum rule in this low-$Q^2$ region with the caveat of the unknown uncertainty attached to the low-$x$ extrapolation. Under this provision, the data are consistent with the sum rule expectation that $\Gamma_x = 0$ for all $Q^2$. They also agree with the earlier results from E94-010 (triangles) [8]. Higher $Q^2$ data from E01-012 (filled squares) [14], RSS (open crosses) [13], and E155x (open square) [4] are also consistent with zero.

In conclusion, $^3$He spin structure functions $g_1(n, Q^2)$, $g_2(n, Q^2)$ and the spin-dependent partial cross-section $\sigma_{\tau\tau}(n, Q^2)$ were measured at low $Q^2$. The moments $\Gamma_{\parallel}(Q^2)$, $\Gamma_{\perp}(Q^2)$ and $\Gamma_{TT}(Q^2)$ of the neutron are extracted at $0.035 \leq Q^2 \leq 0.24$ GeV$^2$. They are compared to two next-to-leading-order $\chi$ EFT calculations from two separate groups, Bernard et al. [41] and Lensky et al. calculation [42]. The $\Gamma_{\parallel}(Q^2)$ and $\Gamma_{TT}(Q^2)$ integrals agree with published data at higher $Q^2$. The data on $\Gamma_{\parallel}(Q^2)$ agree reasonably with both recent $\chi$ EFT calculations. The data on $\Gamma_{TT}(Q^2)$ disagree with the calculation [42] and that of [41] except at the lowest $Q^2$ point. That the results for two recent $\chi$ EFT methods differ, and that they describe with different degrees of success the data underlines the importance of the $\Delta$ degree of freedom for spin observables and the sensitivity of $\chi$ EFT to the consequent $\pi$-$\Delta$ terms. The earlier E94-010 data had triggered improvement of the $\chi$ EFT calculations. Now, the precise E97-110 data, taken in the chiral domain, show that yet further sophistication of $\chi$ EFT is needed before spin observables can be satisfactorily described. Our determination of $\Gamma_{\parallel}(Q^2)$ agrees with the BC sum rule in this low-$Q^2$ region, with the proviso that $g_2^{WW}$ is used to assess the unmeasured low-$x$ part of $\Gamma_{\parallel}$. Analysis of data down to $Q^2 = 0.02$ GeV$^2$ taken at a different time under different conditions, which requires a different analysis, is currently ongoing. These data and results on $\sigma_{\tau\tau}$, the spin polarizabilities $\gamma_1^D$ and $\delta_1^{TT}$, and moments for $^3$He will be reported in future publications. All these data, when combined with results [15] obtained on deuteron and future proton data [47] taken at low $Q^2$, will yield more extensive tests of calculations from $\chi$ EFT, the leading effective theory of strong interactions at low $Q^2$, and eventually to QCD once the lattice QCD calculations of the Compton amplitudes involved in the sum rules becomes available.

Declaration of competing interest

The authors declare that they have no known financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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