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SPIN PHYSICS WITH CLAS AT JEFFERSON LABORATORY

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Abstract

Inelastic scattering using polarized nucleon targets and polarized charged lepton beams allows the extraction of spin structure functions that provide information about the spin structure of the nucleon. A program designed to study such processes at low and intermediate Q^2 for the proton and deuteron has been pursued by the CLAS Collaboration at Jefferson Lab since 1998.

The data with high statistical precision and extensive kinematic coverage allows us to better constrain the polarized parton distributions and to accurately determine various moments of g_1 as a function of Q^2. The latest results are presented, illustrating our contribution to the world data, with comparisons of the data with NLO global fits, phenomenological models, chiral perturbation theory, the GDH and Bjorken sum rules, and tests of global duality.

1 Spin Structure Functions

For several decades spin structure functions have been measured using polarized nucleon targets and polarized lepton beams. In particular, the photon-nucleon asymmetry $A_1^p(x, Q^2)$, the structure function $g_1^p(x, Q^2)$ and its first moment $\Gamma_1(Q^2)$ have been investigated. The photon-nucleon asymmetry $A_1^p(x, Q^2)$ reflects the valence spin structure of the proton. In lowest order

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in the quark parton model, A_1^p is given by the ratio of the spin-dependent to spin-independent quark distribution functions [1]:

$$A_1 = \frac{\Sigma_i e_i^2 [q_i^\uparrow - q_i^\downarrow]}{\Sigma_i e_i^2 [q_i^\uparrow + q_i^\downarrow]}. \tag{1}$$

Assuming that the nucleon obeys SU(6) symmetry at large x generates the prediction that $A_1^p = 5/9$. The symmetry is strongly broken, which is particularly evident at large x. Several non-perturbative mechanisms have been used to account for this observation by explicitly breaking SU(6) at the quark level, which results in different weighting of components of the wavefunction, and consequently different x dependencies for the spin and flavor distributions. Mapping A_1^p as a function of x can help differentiate between the various models.

The spin structure function g_1 is important in understanding the quark and gluon spin components of the nucleon spin, and their relative contributions in different kinematic regions. At high Q^2, g_1 provides information on how the nucleon spin is composed of the spin of its constituent quarks and gluons. At low Q^2, hadronic degrees of freedom become more important and dominate the measurements. Besides its Q^2-dependence, g_1 depends also on the fraction of momentum, x carried by the struck parton. The DGLAP equations [2] predict that g_1^p increases logarithmically with Q^2 at low x, and decreases with Q^2 at high x.

There is particular interest in the first moment of g_1, $\Gamma_1(Q^2) = \int_0^{1^-} g_1(x, Q^2)dx$, which is constrained at low Q^2 by the Gerasimov-Drell-Hearn sum rule [3] and at high Q^2 by the Bjorken sum rule [4] and previous deep inelastic scattering (DIS) experiments. In our definition the upper limit of the integral does not include the elastic peak. Ji and Osborne [5] have shown that the GDH sum rule can be generalized to all Q^2 via

$$S_1(\nu = 0, Q^2) = \frac{8}{Q^2}\left[\Gamma_1(Q^2) + \Gamma_1^{el}(Q^2)\right], \tag{2}$$

where $S_1(\nu, Q^2)$ is the spin-dependent virtual photon Compton amplitude. S_1 can be calculated in Chiral Perturbation Theory (χPT) at low Q^2 and with perturbative QCD (pQCD) at high Q^2. Therefore, Γ_1 represents a calculable observable that spans the entire energy range from hadronic to partonic descriptions of the nucleon.

Another topic of interest is the phenomenon of quark-hadron duality , an observation that the hadronic and partonic degrees of freedom can sometimes both be successfully used to describe the structure of hadrons. This phenomena was discovered experimentally by Bloom and Gilman [6], who observed that the spin averaged structure function $F_2(\nu, Q^2)$ measured in the resonance region was on average equivalent to the 'scaling' deep inelastic one, if averaged over the variable $w' = (2M\nu + M^2)/Q^2$. This phenomenon has recently been studied with high precision in the unpolarized F_2^p structure function [7]. Quark-hadron duality has not been extensively tested in the case of the polarized structure functions.

2 Measurements and Data Analysis

g_1 was extracted from measurements of the double spin asymmetry $A_\parallel$ in inclusive ep scattering:

$$g_1 = \frac{F_1}{1+\gamma^2}[A_\parallel/D + (\gamma - \eta)A_2], \tag{3}$$

where F_1 is the unpolarized structure function, A_2 is the virtual photon asymmetry, and γ, D and η are kinematic factors. F_1 and A_2 are calculated using a parametrization of the world data, and $A_\parallel$ is measured. The spin asymmetry for ep scattering is given by:

$$A_\parallel = \frac{N_- - N_+}{N_- + N_+}\frac{C_N}{fP_bP_tf_{RC}} + A_{RC}, \tag{4}$$

where $N_-(N_+)$ is the number of scattered electrons normalized to the incident charge with negative (positive) beam helicity, f is the dilution factor needed to correct for the electrons scattering off the unpolarized background, f_{RC} and A_{RC} correct for radiative effects, and C_N is the correction factor associated with polarized ^{15}N nuclei in the target. $A_\parallel$ was measured by scattering polarized electrons off polarized nucleons using a cryogenic solid polarized target and CLAS in Hall B. The raw asymmetries were corrected for the beam charge asymmetry, the dilution factor and radiative effects. Since the elastic peak is within the acceptance range, the product of beam and target polarization was determined from the known ep elastic asymmetry.

The longitudinally polarized electrons were produced by a strained $GaAs$ electron source with a typical beam polarization of ∼ 70%. Two solid polarized targets were used: $^{15}ND_3$ for polarized deuterons and $^{15}NH_3$ for polarized protons. The targets were polarized using the method of Dynamic Nuclear Polarization, with the typical polarization of 70-90% for protons, and 10-35% for deuterons. Besides the polarized targets, three unpolarized targets (^{12}C, ^{15}N, liquid ^{4}He) were used for background measurements. The scattered electrons were identified using the CLAS package [8], consisting of drift chambers, Cherenkov detector, time-of-flight counters and electromagnetic calorimeters. Data were taken with beam energies of 1.6, 2.4, 4.2 and 5.7 GeV, covering a kinematic range of $0.05 < Q^2 < 4.5$ GeV^2 and $0.8 < W < 3.0$ GeV. The data include multi-particle final states,making it possible to investigate exclusive and semi-inclusive pion production, deeply virtual Compton scattering and other exclusive channels.

3 Results

3.1 Large x behaviour of $A_1(x, Q^2)$

The photon-nucleon asymmetry A_1^d is shown in Figure 1. Along with the recent CLAS data, the plot shows results from previous experiments, and predictions from several models. The models [9] include the suppression of transitions to states in the lowest even and odd parity multiplets with combined quark spin $S = \frac{3}{2}$, the suppression of transitions to states with helicity $h = \frac{3}{2}$, and the suppression of transitions to the states which couple only through symmetric components of the spin-flavor wavefunction. Also shown is the prediction of the hyperfine-perturbed quark model, which involves spin-spin interaction between quarks, mediated by one gluon or pion exchange [10]. Our data show a preference for the pQCD limit as $x \to 1$, and are also consistent with the hyperfine-perturbed quark model.

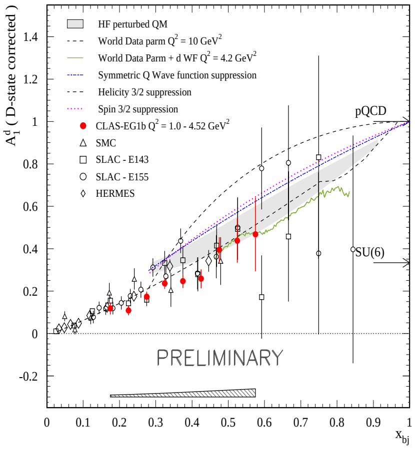

Figure 1: Asymmetry A_1^d plotted vs x could differentiate between the different models of valence spin structure of the nucleons.

3.2 Moments of $g_1(x, Q^2)$

The first moments of g_1^p and g_1^d are shown in Figure 2. The parametrization of world data is used to include the unmeasured contribution to the integral down to $x = 0.001$. Only the Q^2 bins is which the measured part constitutes at least 50% of the total integral are included. For the proton, the parametrization at high x ($1.09 < W < 1.14$ (1.15) GeV is used for the low (high) energy data). For the deuteron, the integration is carried out up to the nucleon pion production threshold at high x, excluding the quasi-elastic and electro- disintegration contributions. The integral is observed to turn over at low Q^2, consistent with the slope predicted by the GDH sum rule. In general the data are well described by the phenomenological models of Burkert and Ioffe [14] and Soffer and Teryaev [15].

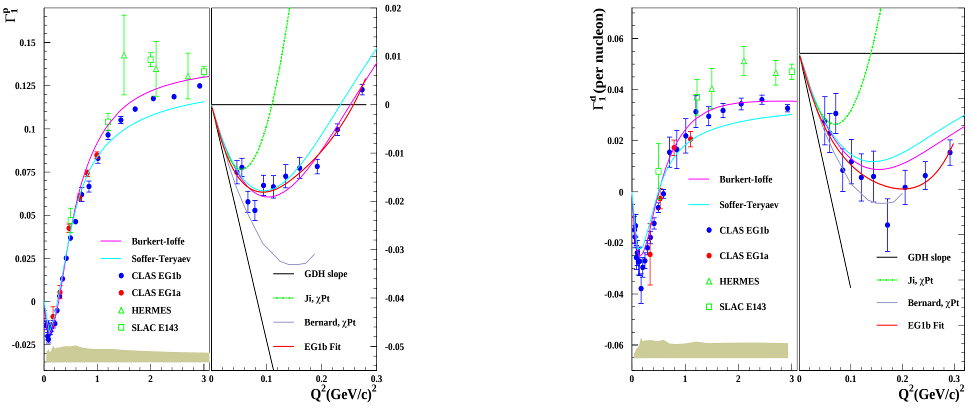

Figure 2: Left: Γ_1^p as a function of Q^2. Right: Γ_1^p as a function of Q^2. The EG1a [11], SLAC [12] and Hermes data [13] are shown for comparison. The filled circles represent the present data, including an extrapolation over the unmeasured part of the x spectrum using a model of world data.

The low Q^2 Γ_1 data are shown in more detail in the right-hand panels of Figs. 2. It is possible to make a quantitative comparison between our results for Γ_1^p and Γ_1^d at low Q^2 and the next-to-leading order χPT calculation by Ji, Kao and Osborne [16], who find $\Gamma_1^p(Q^2) = -\frac{\kappa_p^2}{8M^2}Q^2 + 3.89Q^4 + ...$ and $\Gamma_1^n(Q^2) = -\frac{\kappa_n^2}{8M^2}Q^2 + 3.15Q^4 + ...$ Treating the deuteron as the incoherent sum of a proton and a neutron and correcting for the D-state,

$$\Gamma_1^d(Q^2) = \frac{1}{2}(1 - 1.5\omega_D)\left\{\Gamma_1^p(Q^2) + \Gamma_1^n(Q^2)\right\}, \tag{5}$$

one finds that $\Gamma_1^d(Q^2) = -0.451Q^2 + 3.26Q^4$. The low Q^2 results for Γ_1^p and Γ_1^d have been fit to a function of the form $aQ^2 + bQ^4 + cQ^6 + dQ^8$ where a is fixed at -0.455 (proton) and -0.451 (deuteron) by the GDH sum rule. For the proton, $b = 3.81 \pm 0.31$ (stat) $+0.44 - 0.57$ (syst) is extracted and for the deuteron, $b = 2.91 \pm 0.52$ (stat) ± 0.69 (syst) was obtained, both consistent with the Q^4 term predicted by Ji *et al.*

Our fit is shown in the right-hand panel of plots in Figs. 2 along with Ji's prediction. We find that the Q^6 term becomes important even below $Q^2 = 0.1$ GeV^2 and that this term needs to be included in the χPT calculations in order to extend the range of their validity beyond roughly $Q^2 = 0.06$ GeV^2.

3.3 Test of global duality

The data for both the proton and the deuteron were used to examine quark-hadron duality in g_1.

The test is performed by averaging both data and DIS models for g_1 over a Q^2-dependent interval corresponding to the resonance region, and comparing the two. The averages were determined as

$$< g_1(Q^2) >= \frac{\int_{x_l}^{x_h} g_1(x, Q^2)dx}{x_h - x_l}, \tag{6}$$

where x_l and x_h correspond respectively to the maximum and minimum values of W in the considered interval, at a given value of Q^2 (using the definition $x^{-1} = 1 + (W^2 - M^2)/Q^2$. The x-averaged values of g_1 for the entire resonance region (scaled by Q^2) are plotted as a function of Q^2 in Figure 3 for both targets. Hatched bands represent the range of the averages calculated with the next-to-leading order twist-2 PDF predictions [17], [18]. Each version of the pQCD calculation has been corrected for the target mass effects [19], taking into account the fact that the measurements were taken at a low Q^2. The data for both targets exhibit a power-law-type deviation from the scaling curves at low Q^2, but show good agreement above Q^2=1.7 GeV^2/c^2 within the systematic errors of the data and models. The onset of duality in this happens at a slightly higher value than it does in the case of spin-averaged structure function [7]. An effect of adding the elastic contribution to the numerator was also tested, with the elastic contribution evaluated from the elastic form factors [20]. Inclusion of elastic contribution extends the region of agreement to a lower Q^2 = GeV^2/c^2. The results are similar in case of g_1^p and g_1^d, indicating no large effects from different isospin projections [21].

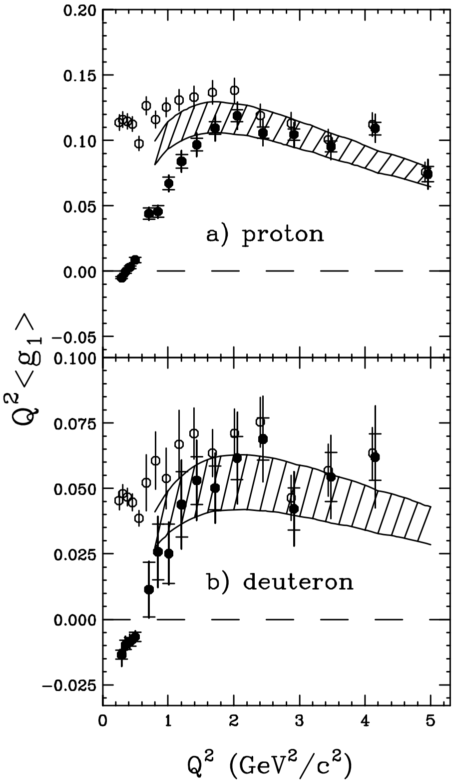

Figure 3: The Q^2-dependence of $Q^2 g_1(x, Q^2)$ averaged over a region in x corresponding to 1.08 < W < 2 GeV (solid circles) for a)proton; b)deuteron. the open circles represent our data after adding the contribution from *ep* elastic (*ed* quasi-elastic) scattering at x = 1 for the proton (deuteron).

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