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EXPERIMENTAL EVIDENCE FOR QUARK–HADRON DUALITY IN SPIN STRUCTURE FUNCTION*

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First results on quark–hadron duality in the spin sector from the HERMES experiment are reported in the range $1.2 \leq Q^2 \leq 12\,\mathrm{GeV}^2$ and $1 \leq W^2 \leq 4\,\mathrm{GeV}^2$.

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1. Introduction and experimental overview

The structure and the interaction of hadrons is generally described by two different but complementary approaches: the quark–gluon context at high energy, where the quarks are asymptotically free, and the meson and baryon description at low energy, where the effects of the confinement are large. In some specific cases where the natural description in terms of hadrons should be applied, the quark–gluon description can be successfully also used. This evidence is called quark–hadron duality and it was introduced by Bloom and Gilman [1]. They observed that the electro-production of nucleon resonances resembles the scaling behavior of the deep inelastic structure function, if expressed in terms of a scaling variable connecting the two different kinematic regions and if averaged over a large range of squared invariant mass $W^2 = M^2 + 2M\nu - Q^2$ (here Q^2 is the squared transfered four-momentum, M is the proton mass and ν the energy of the exchanged virtual photon).

In the past 20 years substantial progress has been made in understanding QCD and the scaling behavior of F_2. Recently from JLAB [2] a sample of inclusive electron–nucleon scattering data have been analyzed for precision tests of quark–hadron duality. Experimentally the duality in F_2 is observed to hold for local enhancements individually, as well as for the

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entire resonance region $1 \leq W^2 \leq 4$ GeV^2 starting from $Q^2 \sim 1.5$ GeV^2. This relation called duality can be "naturally" extended to the polarized case, substituting the unpolarized structure function F_2 with the polarized structure function g_1. Even though duality was observed for the unpolarized structure functions, there is no *a priori* reason to believe that duality also holds for polarized structure functions. In fact, duality is expected to fail for polarized structure functions at low-Q^2, since for the proton the Ellis–Jaffe sum rule and the Gerasimov–Drell–Hearn (GDH) sum rule (at $Q^2 = 0$) are positive and negative, respectively [3]. The interest for the duality in the polarized case started recently [4]. No information is at the moment available on the possible quark–hadron duality in the spin structure function g_1.

2. Analysis procedure and results

The data were collected by the HERMES experiment in 1997 with 27.56 GeV longitudinally polarized positron beam incident on a longitudinally polarized ^{1}H gas target internal to the HERA storage ring at DESY. Scattered positrons were detected by the HERMES spectrometer [5]. The kinematic requirements on the scattered positrons for the analysis in the nucleon resonance region were: $1 \leq W^2 \leq 4\,\mathrm{GeV}^2$, $1.2 \leq Q^2 \leq 12\,\mathrm{GeV}^2$. The corresponding x range was $0.34 < x < 0.98$. After applying data quality criteria, about 120,000 events remained.

The evaluation of the measured longitudinal asymmetry $A_{||}$ is based on the ratio of weighted count rates according to the formula $A_{||} = (N^- L^+ – N^+ L^-)/(N^- L_p^+ + N^+ L_p^-)$ where N is the number of detected scattered positrons, L is the integrated luminosity corrected for dead time, L_p is the integrated luminosity corrected for dead time and weighted by the product of the beam and target polarizations. The superscript $+$ ($-$) refers to the situation where the target spin axis was oriented parallel (anti-parallel) to that of the positron beam.

The limited W resolution in the resonance region ($\delta W \approx 240\,\mathrm{MeV}$) does not allow individual nucleon resonances to be distinguished or the DIS and resonance regions to be completely separated. To evaluate the smearing correction and the contaminations in the resonance region from the elastic and deep-inelastic regions, these effects were studied using a simulation of events from elastic, resonance and deep-inelastic processes. The parameterizations of these contributions were taken from Refs. [6–8]. The "true" value of $A_{||}^{\mathrm{res}}$ is obtained from the relation: $A_{||}^{\mathrm{meas}} = A_{||}^{\mathrm{res}} f_{\mathrm{res}} + A_{||}^{\mathrm{DIS}} f_{\mathrm{DIS}} + A_{||}^{\mathrm{el}} f_{\mathrm{el}}$ where $f_{\mathrm{el,res,DIS}}$ denote the contaminations from corresponding kinematic regions to the resonance one. The contamination from elastic and DIS events in the resonance region varies from 9% to 3.8% and from 10% to 18.5%, respectively, with Q^2 ranging from 1.2 to 12 GeV^2.

2.1. The spin asymmetry A_1

The virtual photo-absorption asymmetry A_1 was extracted from the measured longitudinal asymmetry $A_{||}$ using the relation $A_1 = A_{||}/D - \eta A_2$, where D is the virtual photon depolarization factor and η is a kinematic factor. The contribution of the asymmetry A_2 is taken into account as $A_2 = 0.06 \pm 0.16$ as obtained from SLAC [9] at $Q^2 = 3\,\mathrm{GeV}^2$. In Fig. 1 (left) the spin asymmetry in the nucleon resonance region A_1^{res} is shown as function of x. For each value of x the quantity A_1^{res} has been averaged over Q^2. The total systematic uncertainty of the data is about 16% with the dominant contribution originating from A_2 amounting to 14%. The experimental systematic uncertainty is about 8%. Other contributions are the uncertainties from beam and target polarization (5.3%) and from the spectrometer geometry (2.5%). Contributions from radiative corrections, calculated using the POLRAD code [10], gave a contribution of about 3% to the systematic uncertainty. The extracted spin asymmetry A_1^{res} increases with x. The data indicate that A_1^{res} may exceed the SU(6) prediction of 5/9 at $x = 1$. The experimental behavior at large x is in better agreement with the prediction of a broken SU(6) symmetry due to the hyperfine perturbations of the quark model [11].

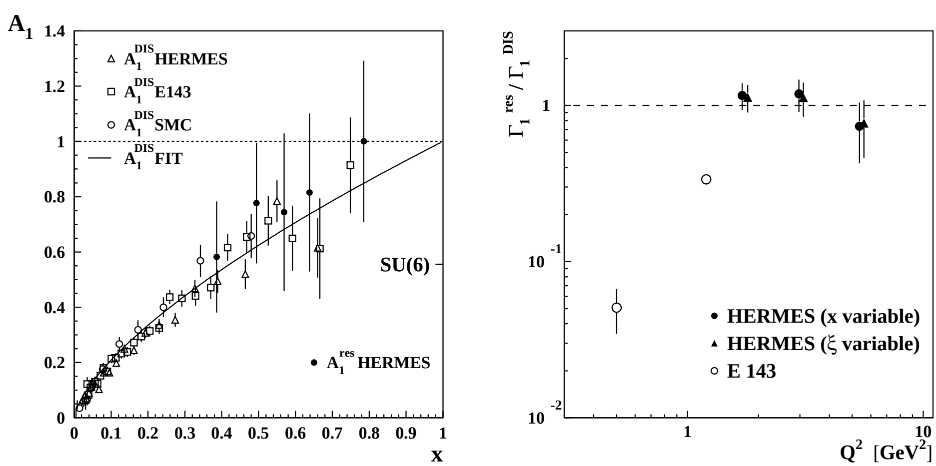

Fig. 1. (Left) Spin asymmetry A_1 as a function of x. The curve represents a fit to DIS data at large x. (Right) Ratio between Γ_1 in the resonance region and Γ_1 in DIS region as a function of Q^2. The data are shown using x (full circles) or ξ (full triangles) as integration parameter. Points in ξ are slightly shifted to make them more visible. See text for details for both figures.

Also shown in Fig. 1 (left) is the asymmetry $A_1^{\rm DIS}$ as measured in DIS [9, 12, 13]. As it is seen the A_1 measured in the resonance region is in agreement within the experimental error with previous DIS data at higher Q^2 and W^2. The curve is a fit on world DIS data at $x > 0.3$, $A_1 = x^{0.68}$. This parameterization of A_1 is constraint to 1 at $x = 1$ and does not depend on Q^2. The average ratio of the measured $A_1^{\rm res}$ to the DIS fit is $1.15 \pm 0.16 \pm 0.18$. This suggests that the description of the spin asymmetry in terms of quark degrees of freedom is also valid in the nucleon resonance region for the Q^2 range explored by the present experiment.

2.2. Q^2 dependence of duality in the structure function g_1

The verification of the quark–hadron duality can be obtained comparing the integrals of the polarized structure function g_1 in the resonance and DIS region in the same x interval. The integrals $\Gamma_1 = \int_{x_{\rm min}}^{x_{\rm max}} g_1(x)\, dx$ have been evaluated separately for the resonance and DIS domains. The selected data have been divided in three bins in Q^2 ($1.2 \leq Q^2 < 2.4$, $2.4 \leq Q^2 < 4$, and $4 \leq Q^2 \leq 12\,{\rm GeV}^2$) and integrated over the whole resonance region ($1 < W^2 < 4\,{\rm GeV}^2$). In each Q^2 bin all the average variables were calculated weighted by the event distribution. The x-ranges covered by the three Q^2 bins were 0.35–0.94, 0.49–0.96, and 0.63–0.98, respectively.

For each bin the integral $\Gamma_1^{\rm res}$ has been calculated using the relation $g_1(x) = A_1^{\rm res} F_1(x)$ to account for the x dependence of the integrand F_1 within the individual x bins. The unpolarised structure function $F_1 = F_2(1+\gamma^2)/(2x(1+R))$ was calculated from a modification of the parameterisation [7] of F_2 that accounts for nucleon-resonance excitation and assuming $R = 0.18$ in the whole W^2 region considered. The limits of integration $x_{\rm max}$ and $x_{\rm min}$ were calculated in each Q^2 bin from the $W^2_{\rm min}$ and $W^2_{\rm max}$ respectively.

The integral $\Gamma_1^{\rm DIS}$ was calculated in the same x range and at the same Q^2 values as for $\Gamma_1^{\rm res}$. The value of $A_1^{\rm DIS}$ was taken from the Q^2 independent fit to DIS data at large x, the unpolarised structure function F_2 was taken from Ref. [8], and the value of R from Ref. [14].

The ratio $\Gamma_1^{\rm res}/\Gamma_1^{\rm DIS}$ for several Q^2 values is shown in Fig. 1 (right). Also shown is the ratio $\Gamma_1^{\rm res}/\Gamma_1^{\rm DIS}$ evaluated from the SLAC data which was evaluated by dividing the measured value of $\Gamma_1^{\rm res}$ [9] by $\Gamma_1^{\rm DIS}$ calculated in the same way as for the present data.

In addition to the total systematic uncertainty for the spin asymmetry $A_1^{\rm res}$, other sources contribute as well to the systematic uncertainty of the ratio $\Gamma_1^{\rm res}/\Gamma_1^{\rm DIS}$. The uncertainty in the knowledge of $F_2^{\rm DIS}$ and R are 2%. The effect of using different parameterisations for $A_1^{\rm DIS}$ for the calculation of the contamination coming from the DIS region and for the evaluation of the integral $\Gamma_1^{\rm DIS}$ contributes up to 7%, while the effect of using different parameterisations for $F_2^{\rm res}$ ranges up to 10%. Taken together the total systematic uncertainty on $\Gamma_1^{\rm res}/\Gamma_1^{\rm DIS}$ amounts to 20%.

The Bjorken variable x is sometimes replaced by the Nachtmann variable $\xi = 2x/(1+\sqrt{1+\gamma^2})$ [15], which includes the target-mass corrections. For high Q^2, ξ approaches x, which is the scaling variable at large Q^2. The ratio $\Gamma_1^{\rm res}/\Gamma_1^{\rm DIS}$ using the Nachtmann variable ξ as integration variable is also shown in Fig. 1 (right). For the integral $\Gamma_1^{\rm res}$, the $F_2^{\rm res}$ parameterisation from JLAB [2] has been used, where a fit to the average strength of all the proton resonance spectra has been obtained and used as a scaling curve. No large effects due to target mass corrections are observed.

In conclusion, the first experimental evidence of quark–hadron duality for the polarised structure function g_1 on the proton has been presented for Q^2 values larger than 1.7 GeV^2. The spin asymmetries measured in the nucleon resonance region have been found to be in agreement with the spin asymmetries measured in the DIS region at larger W^2. This experimental finding indicates that the description of the spin asymmetry in terms of quark degrees of freedom is valid also in the nucleon resonance region within the kinematic range probed by the present experiment. The quark–hadron duality for the polarised structure function g_1 has been found satisfied at a similar Q^2 as for the unpolarised structure function F_2.

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