Evidence for Quark-Hadron Duality in the Proton Spin Asymmetry A_1

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Spin-dependent lepton-nucleon scattering data have been used to investigate the validity of the concept of quark-hadron duality for the spin asymmetry A_1. Longitudinally polarized positrons were scattered off a longitudinally polarized hydrogen target for values of Q^2 between 1.2 and 12 GeV^2 and values of W^2 between 1 and 4 GeV^2. The average double-spin asymmetry in the nucleon resonance region is found to agree with that measured in deep-inelastic scattering at the same values of the Bjorken scaling variable x. This finding implies that the description of A_1 in terms of quark degrees of freedom is valid also in the nucleon resonance region for values of Q^2 above 1.6 GeV^2.

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The interaction between baryons and leptons can generally be described by two complementary approaches: with quark-gluon degrees of freedom at high energy, where the quarks are asymptotically free, and in terms of hadronic degrees of freedom at low energy, where effects of confinement are large. In some specific cases, where the description in terms of hadrons is expected to apply most naturally, the quark-gluon description can also be successfully used. Such cases are examples of so-called quark-hadron duality. Bloom and Gilman [1] first noted this relationship between phenomena in the nucleon resonance region and in deep-inelastic scattering (DIS). Specifically, they observed that the cross section for electroproduction of nucleon resonances, if averaged over a large enough range of invariant mass W of the initial photon-nucleon system, exhibited the same behavior as the cross section observed in the DIS region. In other words, the scaling limit curve measured as a function of the variable $x' = x + M^2/Q^2$ in DIS processes at high Q^2 and high ν approximately approaches the smooth curves derived from measurements in the resonance region at lower ν and Q^2 (here $x = Q^2/2M\nu$ is the Bjorken scaling variable, $-Q^2$ is the four-momentum transfer squared, M is the proton mass, and ν is the energy of the exchanged virtual photon in the target rest frame).

Duality in strong interaction physics was originally formulated for hadron-hadron scattering [2]: the high-energy behavior of amplitudes, described within Regge theory in terms of t-channel Regge pole exchanges, was related to the behavior of the amplitudes at low energy, which are well described by a sum over a few s-channel resonances [3,4]. In QCD the Bloom-Gilman duality can be interpreted in the language of the operator product expansion in which moments of structure functions are expanded in powers of $1/Q$ [5,6]. The leading terms are associated with noninteracting partons and exhibit scaling, while the terms proportional to $1/Q$ involve interactions between quarks and gluons. While the first moments of the structure functions depend weakly on Q^2, this is not true for the higher moments, since at large x the scaling violations of structure functions (i.e., the Q^2 dependence for fixed values of x) are very large, so that a leading order description in terms of parton distributions is unable to reproduce DIS data. Therefore, additional terms, which effectively account for higher-order, higher-twist, and target-mass corrections, should be included. It has been shown that in that way a good description of measured values of F_2 structure function over a wide range of Q^2 and x can be obtained [7].

Recently, a sample of inclusive unpolarized electron-nucleon scattering data on hydrogen and deuterium targets has been analyzed to investigate the validity of quark-hadron duality [8]. For the proton, it was observed that starting from $Q^2 \geq 1.5$ GeV^2 duality in the unpolarized structure function F_2 holds for individual resonance contributions, as well as for the entire resonance region $1 \leq W^2 \leq 4$ GeV^2. It is worthwhile to mention that duality in the unpolarized structure function holds only when comparing the data in the resonance region with phenomenological fits to DIS data, while it does not hold when comparing with QCD fits at leading order only.

In contrast to the extensive study of duality for the unpolarized, i.e., spin-averaged, photoabsorption cross section, the validity of duality has not been investigated for the spin-dependent scattering processes, which are related to the spin-dependent photoabsorption cross section. Observation of duality for the spin asymmetry A_1 is of particular interest as it may lead to a complementary means to study the spin structure of the nucleon at large x, which is difficult to measure in the DIS region with high statistics. Since the DIS spin asymmetry A_1 has been found to be independent of Q^2 for all measured values of x, the comparison of this asymmetry in the resonance and in the DIS regions is straightforward and does not depend on the choice of the parametrization of DIS cross section data.

In this Letter the first experimental evidence for quark-hadron duality for the proton spin asymmetry A_1 is reported. The data were collected by the HERMES experiment in 1997 with a 27.57 GeV longitudinally polarized positron beam incident on a longitudinally polarized hydrogen gas target internal to the lepton storage ring of the Hadron Electron Ring Accelerator (HERA) at DESY. The positrons in the HERA ring are transversely polarized by emission of synchrotron radiation [9]. Longitudinal polarization is obtained by using spin rotators located upstream and downstream of the HERMES experiment [10]. The beam polarization was measured continuously using Compton backscattering of circularly polarized laser light [11]. The average beam polarization for the analyzed data was 0.55 with a relative systematic uncertainty of 3.4%.

The HERMES polarized target [12] consists of polarized atomic hydrogen gas confined in a storage cell, fed by an atomic-beam source of nuclear-polarized hydrogen based on Stern-Gerlach separation [13]. The nuclear polarization of the atoms and the atomic fraction are continuously measured with a Breit-Rabi polarimeter [14] and a target gas analyzer. The average target polarization for the analyzed data was 0.88 with a relative systematic uncertainty of 4.7% [15].

Scattered positrons were detected by the HERMES spectrometer, described in Ref. [16]. For all detected positrons the angular resolution was better than 0.6 mrad, the momentum resolution was better than 1.6% aside from bremsstrahlung tails, and the Q^2 resolution was better than 2.2%.

In addition to the constraints of the acceptance of the HERMES spectrometer, the kinematic requirements for the analysis in the nucleon resonance region were $1 \leq W^2 \leq 4\ \mathrm{GeV}^2$ and $1.2 \leq Q^2 \leq 12\ \mathrm{GeV}^2$. The corresponding x range was $0.34 < x < 0.98$. After applying data quality criteria, about 120 000 events remained.

The evaluation of the longitudinal asymmetry $A_\parallel$ is based on the ratio of the luminosity weighted (i.e., normalized) count rates using the following formula:

$$A_\parallel = \frac{N^{\overset{\rightarrow}{\Leftarrow}} L^{\overset{\rightarrow}{\Rightarrow}} - N^{\overset{\rightarrow}{\Rightarrow}} L^{\overset{\rightarrow}{\Leftarrow}}}{N^{\overset{\rightarrow}{\Leftarrow}} L_{\mathrm{P}}^{\overset{\rightarrow}{\Rightarrow}} + N^{\overset{\rightarrow}{\Rightarrow}} L_{\mathrm{P}}^{\overset{\rightarrow}{\Leftarrow}}},$$

where N is the number of detected scattered positrons, L is the integrated luminosity corrected for dead time, and L_{P} is the integrated luminosity corrected for dead time and weighted by the product of the beam and target polarizations. The superscript $\overset{\rightarrow}{\Rightarrow}$ ($\overset{\rightarrow}{\Leftarrow}$) refers to the orientation of the target spin parallel (antiparallel) to the positron beam polarization.

The limited W resolution in the resonance region ($\delta W \approx 240$ MeV) does not allow individual nucleon resonances to be distinguished nor the DIS ($W > 2$ GeV) and resonance ($W \leq 2$ GeV) 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 parametrizations of these contributions were taken from Refs. [17–19]. The contamination from elastic and DIS events in the resonance region varies from 9.7% to 3.3% and from 9.5% to 18.7%, respectively, with Q^2 ranging from 1.2 to 12 GeV^2.

The virtual photoabsorption asymmetry A_1 is proportional to the cross section difference $(\sigma_{1/2} - \sigma_{3/2})$, where $\sigma_{1/2}$ and $\sigma_{3/2}$ are the photoabsorption cross sections for total helicities 1/2 and 3/2, respectively. The asymmetry A_1 was extracted [20] from the measured longitudinal asymmetry $A_\parallel$ using the relation $A_1 = A_\parallel / D - \eta A_2$, where D is the virtual photon depolarization factor and η is a kinematic factor [21]. It is noted that the quantity D depends on the ratio $R = \sigma_L/\sigma_T$ of absorption cross sections for longitudinal and transverse virtual photons [22]. The asymmetry A_2 is related to the structure function $g_2(x)$ by $A_2 = \gamma[g_1(x) + g_2(x)]/\mathrm{F}_1(x)$, where $\gamma^2 = Q^2/\nu^2$. The asymmetry A_1 was calculated under the assumption that $A_2 = 0.06 \pm 0.16$ as obtained from SLAC measurements [23] at $Q^2 = 3\ \mathrm{GeV}^2$.

The spin asymmetry in the nucleon resonance region A_1^{res} is given in Table I and is shown as a function of x in Fig. 1. For each value of x the quantity A_1^{res} has been averaged over Q^2. The average Q^2 ranges from 1.6 GeV^2 in the lowest x bin to 2.9 GeV^2 in the highest. The total systematic uncertainty of the data is about 16%, with the dominant contribution originating from A_2 amounting to 14%. This contribution was evaluated using the measured uncertainty of A_2 quoted above. The uncertainty of 14% is also consistent with the assumption that $A_2 = 0$, and the assumption that $A_2 = 0.53 Mx/\sqrt{Q^2}$, which describes its behavior in the deep-inelastic region [15]. The experimental systematic uncertainty receives a total contribution of about 8% from the following sources. The resolution smearing effects give contributions up to 5.6%. They were evaluated by comparing simulated

TABLE I. Spin asymmetry in the nucleon resonance region A_1^{res} as a function of the Bjorken variable x and of the Nachtmann variable ξ. For each value, the average Q^2 is also given. $\delta A_1^{\mathrm{res}}$ represent the statistical uncertainties; the systematic uncertainty for the data is about 16%.

x	ξ	$\langle Q^2 \rangle$ (GeV^2)	$A_1^{\mathrm{res}} \pm \delta A_1^{\mathrm{res}}$
0.38	0.36	1.6	0.46 ± 0.20
0.50	0.45	2.0	0.77 ± 0.21
0.57	0.51	2.3	0.88 ± 0.29
0.64	0.57	2.6	0.76 ± 0.28
0.78	0.68	2.9	0.99 ± 0.29

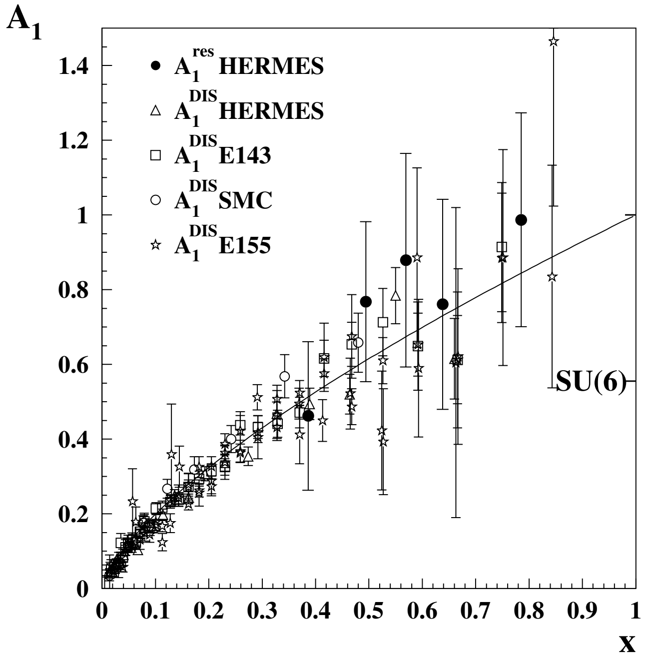

FIG. 1. Spin asymmetry A_1 as a function of x measured in the resonance region (full circles). Error bars represent the statistical uncertainties; the systematic uncertainty for the data in the resonance region is about 16%. Open symbols are previous results obtained in the DIS region. The curve represents a power law fit to DIS data at $x > 0.3$.

results from two very different assumptions for A_1, a power law ($A_1^{\rm res} = x^{0.7}$), and a step function ($A_1^{\rm res} = -0.5$ for $W^2 < 1.8\ {\rm GeV}^2$ and $A_1^{\rm res} = 1.0$ for $1.8 \leq W^2 \leq 4.0\ {\rm GeV}^2$), which is suggested by the hypothesis of the possible dominance of the P_{33} resonance at low W^2 and the S_{11} at higher W^2. The modification of the depolarization factor D due to smearing effects was also taken into account. 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 [24], gave a contribution of up to 3% to the systematic uncertainty.

Also shown in Fig. 1 is the asymmetry $A_1^{\rm DIS}$ as measured in DIS [15,23,25,26]. The data in the resonance region are in agreement with those measured in DIS. The data indicate that $A_1^{\rm res}$ may exceed the exact spin-flavor SU(6) symmetry expectation of 5/9 at $x = 1$, being in better agreement with the original and long-standing prediction of 1 at $x = 1$ [27]. This latter prediction is also favored by the measured $A_1^{\rm DIS}$ at large x and by more recent expectations [28–30]. The curve in Fig. 1 is a power law fit to the world DIS data at $x > 0.3$: $A_1^{\rm DIS} = x^{0.7}$. This parametrization of A_1 is constrained to 1 at $x = 1$ and does not depend on Q^2, as indicated by experimental data in this range [26]. The average ratio of the measured $A_1^{\rm res}$ to the DIS fit is 1.11 ± 0.16 (stat.) $\pm$ 0.18 (syst.).

Originally, duality was introduced by Bloom and Gilman [1] by considering the variable $x' = x + M^2/Q^2$ instead of the Bjorken variable x, while more recently the Nachtmann variable $\xi = 2x/(1 + \sqrt{1 + \gamma^2})$ [31] was generally used for duality studies [8]. The latter variable accounts for the effects of the mass of the target which are not negligible in the nucleon resonance excitation kinematics. In Table I, the relevant values for the Nachtmann variable ξ are reported together with the ones for the Bjorken variable x. The difference between the two variables amounts to about 10% in the HERMES kinematics and this difference results in a small target-mass correction of about 5% to the ratio of $A_1^{\rm res}$ to $A_1^{\rm DIS}$.

These results suggest that the description of the spin asymmetry in terms of quark degrees of freedom is valid also in the nucleon resonance region for the Q^2 range explored by the present experiment. The evidence for duality in both the spin-averaged and the spin-dependent scattering processes means that the photoabsorption cross sections for the two helicity states ($\sigma_{1/2}$ and $\sigma_{3/2}$) exhibit duality separately.

It is worth mentioning that the measured spin asymmetry in the resonance region for $Q^2 > 1.6\ {\rm GeV}^2$, where the asymmetry is dominated by the $\sigma_{1/2}$ component, is positive and has the opposite sign with respect to the one measured in the real photon limit ($Q^2 = 0$), where the helicity asymmetry of leading resonances is dominated by the $\sigma_{3/2}$ component [32]. Since the measured spin asymmetry in the DIS region is always positive for any Q^2, duality in the spin asymmetry must break down as Q^2 goes to zero. In particular, it has been argued that duality must fail near $Q^2 \sim 0.5\ {\rm GeV}^2$, where the electric and magnetic multipoles in the virtual photoabsorption are expected to have comparable strengths [33].

In summary, the first experimental evidence of quark-hadron duality for the spin asymmetry $A_1(x)$ of the proton has been observed for Q^2 between 1.6 and 2.9 ${\rm GeV}^2$. The spin asymmetries measured in the nucleon resonance region at $W^2 \leq 4\ {\rm GeV}^2$ have been found to be in agreement with the spin asymmetries measured in the DIS region at larger W^2. Target-mass effects are found to be small in the HERMES kinematics. This experimental finding indicates that the description of the spin asymmetry in terms of quark degrees of freedom is on average valid also in the nucleon resonance region within the Q^2 range probed by the present experiment.

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