Physics Letters B 744 (2015) 309–314

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Precision measurements of A_1^n in the deep inelastic regime

The Jefferson Lab Hall A Collaboration

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http://dx.doi.org/10.1016/j.physletb.2015.03.067

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ARTICLE INFO

Article history:
Received 11 December 2014
Received in revised form 18 March 2015
Accepted 31 March 2015
Available online 7 April 2015
Editor: D.F. Geesaman

Keywords:
Spin structure functions
Nucleon structure
Parton distribution functions
Polarized electron scattering

ABSTRACT

We have performed precision measurements of the double-spin virtual-photon asymmetry A_1 on the neutron in the deep inelastic scattering regime, using an open-geometry, large-acceptance spectrometer and a longitudinally and transversely polarized ^{3}He target. Our data cover a wide kinematic range $0.277 \leq x \leq 0.548$ at an average Q^2 value of 3.078 $(\mathrm{GeV/c})^2$, doubling the available high-precision neutron data in this x range. We have combined our results with world data on proton targets to make a leading-order extraction of the ratio of polarized-to-unpolarized parton distribution functions for up quarks and for down quarks in the same kinematic range. Our data are consistent with a previous observation of an A_1^n zero crossing near $x = 0.5$. We find no evidence of a transition to a positive slope in $(\Delta d + \Delta\bar{d})/(d + \bar{d})$ up to $x = 0.548$.

Ever since the European Muon Collaboration determined that the quark-spin contribution was insufficient to account for the spin of the proton [1,2], the origin of the nucleon spin has been an open puzzle; see Ref. [3] for a recent review. Recently, studies of polarized proton–proton collisions have found evidence for a non-zero contribution from the gluon spin [4,5] and for a significantly positive polarization of $\bar{u}$ quarks [6]. The possible contribution of parton orbital angular momentum (OAM) is also under investigation. In the valence quark region, combining spin-structure data obtained in polarized-lepton scattering on protons and neutrons allows the separation of contributions from up and down quarks and permits a sensitive test of several theoretical models.

In deep inelastic scattering (DIS), nucleon structure is conventionally parameterized by the unpolarized structure functions $F_1(x, Q^2)$ and $F_2(x, Q^2)$, and by the polarized structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$, where Q^2 is the negative square of the four-momentum transferred in the scattering interaction and x is the Bjorken scaling variable, which at leading order in the infinite-momentum frame equals the fraction of the nucleon momentum carried by the struck quark. One useful probe of the nucleon spin structure is the asymmetry $A_1 = (\sigma_{1/2} - \sigma_{3/2})/(\sigma_{1/2} + \sigma_{3/2})$, where $\sigma_{1/2(3/2)}$ is the cross section of virtual photoabsorption on the nucleon for a total spin projection of 1/2 (3/2) along the virtual-photon momentum direction. At finite Q^2, this asymmetry may be expressed in terms of the nucleon structure functions as [7]

$$A_1(x, Q^2) = \left[g_1(x, Q^2) - \gamma^2 g_2(x, Q^2)\right] / F_1(x, Q^2), \qquad (1)$$

where $\gamma^2 = 4M^2x^2c^2/Q^2$ and M is the nucleon mass. For large Q^2, $\gamma^2 \ll 1$ and $A_1(x) \approx g_1(x)/F_1(x)$; since g_1 and F_1 have the same Q^2 evolution at leading order and at next to leading order (NLO) [8–10], A_1 may be approximated as a function of x alone. Through Eq. (1), measurements of A_1 on proton and neutron targets also allow extraction of the flavor-separated ratios of polarized to unpolarized parton distribution functions (PDFs), $(\Delta q(x) + \Delta\bar{q}(x))/(q(x) + \bar{q}(x))$. Here, $q(x) = q^{\uparrow}(x) + q^{\downarrow}(x)$ and $\Delta q(x) = q^{\uparrow}(x) - q^{\downarrow}(x)$, where $q^{\uparrow(\downarrow)}(x)$ is the probability of finding the quark q with a given value of x and with spin (anti)parallel to that of the nucleon. This Letter reports a high-precision measurement of the neutron A_1, A_1^n, in a kinematic range where theoretical predictions begin to diverge.

A variety of theoretical approaches predict that $A_1^n \to 1$ as $x \to 1$. Calculations in the relativistic constituent quark model (RCQM), for example, generally assume that SU(6) symmetry is broken via a color hyperfine interaction between quarks, lowering the energy of spectator-quark pairs in a spin singlet state relative to those in a spin triplet state and increasing the probability that, at high x, the struck quark carries the nucleon spin [11].

In perturbative quantum chromodynamics (pQCD), valid at large x and large Q^2 where the coupling of gluons to the struck quark is small, the leading-order assumption that the valence quarks have no OAM leads to the same conclusion about the spin of the struck quark [12,13]. Parameterizations of the world data, in the context of pQCD models, have been made at NLO both with and without this assumption of hadron helicity conservation. The LSS (BBS) parameterization [14] is a classic example of the former; Avakian et al. [15] later extended that parameterization to explicitly include Fock states with nonzero quark OAM. Both parameterizations enforce $A_1^n(x \to 0) < 0$ and $A_1^n(x \to 1) \to 1$ and predict $\lim_{x\to 1}(\Delta d + \Delta\bar{d})/(d + \bar{d}) = 1$. However, the OAM-inclusive parameterization predicts that $(\Delta d + \Delta\bar{d})/(d + \bar{d})$, which is negative at low x, crosses zero at significantly higher x than predicted by LSS (BBS). Recently, the Jefferson Lab Angular Momentum (JAM) Collaboration performed a global NLO analysis at $Q^2 = 1$ $(\mathrm{GeV/c})^2$ to produce a new parameterization [16], and then systematically studied the effects of various input assumptions [17]. Without enforcing hadron helicity conservation, JAM found that the ratio $(\Delta d + \Delta\bar{d})/(d + \bar{d})$ remains negative across all x; regardless of this initial assumption, the existing world data can be fit approximately equally well with or without explicit OAM terms of the form given by Ref. [15]. The scarcity of precise DIS neutron data above $x \approx 0.4$, combined with the absence of such data points for $x \gtrsim 0.6$, leaves the pQCD parameterizations remarkably unconstrained.

The statistical model treats the nucleon as a gas of massless partons at thermal equilibrium, using both chirality and DIS data to constrain the thermodynamical potential of each parton species. At a moderate Q^2 value of 4 $(\mathrm{GeV/c})^2$, $A_1^n(x \to 1) \to 0.6 \cdot \Delta u(x)/u(x) \sim 0.46$ [18]. Statistical-model predictions are thus in conflict with hadron helicity conservation. A modified Nambu–Jona-Lasinio (NJL) model, including both scalar and axial-vector diquark channels, yields a similar prediction for A_1^n as $x \to 1$ [19]. A recent approach based on Dyson–Schwinger equations (DSE) predicts $A_1^n(x = 1) = 0.34$ in a contact-interaction framework, and 0.17 in a more realistic framework in which the dressed-quark mass is permitted to depend on momentum [20]; the latter prediction is significantly smaller than either the statistical or NJL prediction at $x = 1$. However, existing DIS data do not extend to high enough x to definitively favor one model over another.

Measurements of the virtual-photon asymmetry A_1 can be made via doubly polarized electron–nucleon scattering. With both