2015

Precision measurements of $A(1)(n)$ in the deep inelastic regime

D. S. Parno

F. Benmokhtar

G. B. Franklin

T. Averett

*College of William and Mary*

J. Katich

*College of William and Mary*

See next page for additional authors

Follow this and additional works at: [https://scholarworks.wm.edu/aspubs](https://scholarworks.wm.edu/aspubs)

Recommended Citation


This Article is brought to you for free and open access by the Arts and Sciences at W&M ScholarWorks. It has been accepted for inclusion in Arts & Sciences Articles by an authorized administrator of W&M ScholarWorks. For more information, please contact scholarworks@wm.edu.
Precision measurements of $A_{11}$ in the deep inelastic regime

The Jefferson Lab Hall A Collaboration

D.S. Parno a,b,c, D. Flay c,d, M. Posik c, K. Allada e, W. Armstrong c, T. Averett f, F. Benmokhtar a, W. Bertozzi g, A. Camsonne h, M. Canan i, G.D. Cates j, C. Chen k, J.-P. Chen h, S. Choi l, E. Chudakov h, F. Cusano m,n,1, M.M. Dalton k, W. Deconinck g, C.W. de Jager h, J. Deng j, A. Deur h, C. Dutta e, L. E. Fassi o,p, G.B. Franklin a, M. Friend a, H. Gao q, F. Garibaldi m, S. Gilad g, R. Gilman h,o, O. Glamazdin r, S. Golge i, J. Gomez h, L. Guo s, O. Hansen h, D.W. Higinbotham h, T. Holmstrom t, J. Huang g, C. Hyde i,u, H.F. Ibrahim v, X. Jiang o,s, G. Jin j, J. Katich c, A. Kelleher f, A. Kolarkar e, W. Korsch e, G. Kumbartzki o, J.J. LeRose h, R. Lindgren j, N. Liyanage l, E. Long v, A. Lukhanin c, V. Mamyans a, D. McNulty d, Z.-E. Meziani c, R. Michaels h, M. Mihovilović x, B. Moffit g,h, N. Muangma g, S. Nanda h, A. Narayan p, V. Nelyubin j, B. Norum j, Nuruzzaman p, Y. Oh i, J.C. Peng y, X. Qian q,z, Y. Qiang h, A. Rakham a, S. Riordan j,d, A. Saha h,1, B. Sawatzky c,h, M.H. Shabestari f, A. Shahinyan ab, S. Širca ac,x, P. Solvignon ad,h, R. Subedi j, V. Sulkosky g,h, W.A. Tobias j, W. Troth d, D. Wang l, Y. Wang y, B. Wojtsekhowski h, X. Yan e,h, H. Yao c,f, Y. Ye ae, Z. Ye e, L. Yuan k, X. Zhan h, Y. Zhang hf, Y.-W. Zhang af,o, B. Zhao j, X. Zheng j

a Carnegie Mellon University, Pittsburgh, PA 15213, United States
b Center for Experimental Nuclear Physics and Astrophysics and Department of Physics, University of Washington, Seattle, WA 98195, United States
c Temple University, Philadelphia, PA 19122, United States
d University of Massachusetts, Amherst, MA 01003, United States
e University of Kentucky, Lexington, KY 40506, United States
f College of William and Mary, Williamsburg, VA 23187, United States
g Massachusetts Institute of Technology, Cambridge, MA 02139, United States
h Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, United States
i Old Dominion University, Norfolk, VA 23529, United States
j University of Virginia, Charlottesville, VA 22904, United States
k Hampton University, Hampton, VA 23668, United States
l Seoul National University, Seoul 151-742, South Korea
m INFN, Sezione di Roma, I-00161 Rome, Italy
n Istituto Superiore di Sanità, I-00161 Rome, Italy
o Rutgers, The State University of New Jersey, Piscataway, NJ 08855, United States
p Mississippi State University, MS 39762, United States
q Duke University, Durham, NC 27708, United States
r Kharkiv Institute of Physics and Technology, Kharkov 61108, Ukraine
s Los Alamos National Laboratory, Los Alamos, NM 87545, United States
t Longwood University, Farmville, VA 23909, United States
u Université Blaise Pascal/LN2P3, F-63177 Aubière, France
v Cairo University, Giza 12613, Egypt
w Kent State University, Kent, OH 44242, United States
x Jožef Stefan Institute, Ljubljana, Slovenia
y University of Illinois at Urbana-Champaign, Urbana, IL 61801, United States
z Los Alamos National Laboratory, Los Alamos, NM 87545, United States
a4 Syracuse University, Syracuse, NY 13244, United States
a5 Yerevan Physics Institute, Yerevan 375036, Armenia

* Corresponding author at: Center for Experimental Nuclear Physics and Astrophysics, Box 354290, University of Washington, Seattle, WA 98195, United States. Tel: +1 206 543 4035; fax: +1 206 685 4634.
E-mail address: dparno@uw.edu (D.S. Parno).

1 Deceased.

http://dx.doi.org/10.1016/j.physletb.2015.03.067
0370-2693 © 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP3.
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 nonzero 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 photon absorption 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]

$$A_1(x, Q^2) = \left[\frac{g_1(x, Q^2) - \gamma^2 g_2(x, Q^2)}{F_1(x, Q^2)}\right],$$

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), $(\Delta g(x) + \Delta \bar{g}(x))/(q(x) + \bar{q}(x))$. Here, $q(x) = q^1(x) + q^2(x)$ and $\Delta q(x) = \Delta q^1(x) - \Delta q^2(x)$, where $\Delta q^{1,2}(x)$ 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 $Q^2 = 1$ (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 $x \geq 0.6$, 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 (GeV/c)^2, $A_1^N(x \to 1) \to 0.6 - \Delta u(x)/u(x) \sim 0.46$ [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
beam and target polarized longitudinally with respect to the beamline, $A_l = (\sigma^{+\theta} - \sigma^{-\theta})/(\sigma^{+\phi} + \sigma^{-\phi})$ is the scattering asymmetry between configurations with the electron spin anti-aligned ($\downarrow$) and aligned ($\uparrow$) with the beam direction. Meanwhile, $A_{\perp} = (\sigma^{+\theta} - \sigma^{-\theta})/(\sigma^{+\phi} + \sigma^{-\phi})$ is measured with the target spin oriented horizontally, perpendicular to the incident beam direction and on the side of the scattered electron. $A_1$ may be related to these asymmetries through [7]:

$$A_1 = \frac{1}{D (1 + \eta E)} A_{\parallel} - \frac{\eta}{D (1 + \eta E)} A_{\perp},$$

where the kinematic variables are given in the laboratory frame by $D = (E - E')/(E(1 + \epsilon))$, $\eta = \epsilon \sqrt{Q^2/(E - E')}$, $d = D \sqrt{2E_{f}(1 + \epsilon)}$, and $\epsilon = \eta(1 + \epsilon)/2\epsilon$. Here, $E$ is the initial electron energy; $E'$ is the scattered electron energy; $\epsilon = 1/[1 + 2(1 + 1/\gamma^2)\tan^2(\theta/2)]$; $\theta$ is the electron scattering angle, shown in Fig. 1; and $R = \sigma_l/\sigma_T$, parameterized via R1998 [21], is the ratio of the longitudinal to the transverse virtual photoabsorption cross sections.

Experiment E06-014 ran in Hall A of Jefferson Lab in February and March 2009 with the primary purpose of measuring a twist-3 matrix element of the neutron [22]. Longitudinally polarized electrons were generated via illumination of a strained superlattice GaAs photocathode by circularly polarized laser light [23] and delivered to the experimental hall with energies of 4.7 and 5.9 GeV. The rastered 12–15 μA beam was incident on a target of $^3$He gas [24], polarized in the longitudinal and transverse directions via spin-exchange optical pumping of a Ra–K mixture [25] and contained in a 40-cm-long glass cell. The left high-resolution spectrometer [26] and BigBite spectrometer [27] independently detected scattered electrons at angles of 45° on beam left and right, respectively.

The longitudinal beam polarization was monitored continuously by Compton polarimetry [28,29] and intermittently by Möller polari-

metry [30]. In three run periods with polarized beam, the longitudinal beam polarization $P_l$ averaged 0.74±0.01 ($E = 5.9$ GeV), 0.79±0.01 ($E = 5.9$ GeV), and 0.63±0.01 ($E = 4.7$ GeV). A feedback loop limited the charge asymmetry to within 100 ppm. The target polarization $P_t$, averaging about 50%, was measured periodically using nuclear magnetic resonance [31] and calibrated with electron paramagnetic resonance; in the longitudinal orientation, the calibration was cross-checked with nuclear magnetic resonance data from a well-understood water target.

The raw asymmetry $A_{raw}^{\perp(\parallel)}$ was corrected for beam and target effects according to $A_{corr}^{\perp(\parallel)} = A_{raw}^{\perp(\parallel)}/(P_l P_t F_{0}\cos(\phi))$. The dilution factor $F_{0} \approx 0.920 \pm 0.003$, determined from dedicated measurements with a nitrogen target and found to be approximately constant across our x range, corrects for scattering from the small amount of $^3$He gas added to the $^3$He target to reduce depolarization effects [32]. The angle $\phi$, which appears in $A_{corr}^{\perp(\parallel)}$, is defined in Fig. 1.

Data for the asymmetry measurements were taken with the BigBite detector stack, which in this configuration included eight-
A detailed discussion of the radiative corrections may be found in Ref. [45].

Polarized \(^3\)He targets are commonly used as effective polarized neutron targets because, in the dominant spin state, the spin of the \(^3\)He nucleus is carried by the neutron. To extract the neutron asymmetry \(A^1_n\) from the measured asymmetry \(A^1\)\(^3\)He on the nuclear target, we used a model for the \(^3\)He wavefunction incorporating \(S\), \(S'\), and \(D\) states as well as a pre-existing \(\Delta(1232)\) component [46]:

\[
A^1_n = \frac{F^3\text{He}}{F^1\text{He}} \left( A^1\text{He} - 2 \frac{F^0}{F^1}\text{He} P_{\pi} A^2 \left( 1 - \frac{0.014}{2P_{\pi}} \right) \right). \tag{4}
\]

The effective proton and neutron polarization parameters were taken as \(P_{\pi} = -0.025^{+0.006}_{-0.004}\) and \(P_{\pi} = 0.860^{+0.036}_{-0.020}\) [47]. \(F_2\) was parameterized with F1F209 [35] for \(^3\)He and with CJ12 [48] for the neutron and proton, while \(A^1_p\) was modeled with a \(Q^2\)-independent, three-parameter fit to world data [1,2,3,49-53] on proton targets. Eq. (4) was applied separately to the data from the two beam energies, at the measured average \(Q^2\) values of 2.59 \((\text{GeV}/c)^2\) \((E = 4.7 \text{ GeV})\) and 3.67 \((\text{GeV}/c)^2\) \((E = 5.9 \text{ GeV})\). The resulting neutron asymmetry, the statistics-weighed average of the asymmetries measured at the two beam energies, is given as a function of \(x\) in Fig. 2 and Table 2 and corresponds to an average \(Q^2\) value of 3.078 \((\text{GeV}/c)^2\). Table 2 also gives our results for the structure-function ratio \(g_1^u/F_1\) \([\gamma(1 - \epsilon R)]/(1 - \epsilon(2 - y))\) \(/[A_1 + \tan(\theta/2)A_{1\perp}]\), where \(y = (E - E')/E\) in the laboratory frame. This ratio was extracted from our \(^3\)He data in the same way as \(A^1\).

Combining the neutron \(g_1/F_1\) data with measurements on the proton allows a flavor decomposition to separate the polarized-to-unpolarized-PDF ratios for up and down quarks, giving greater sensitivity than \(A^1_p\) to the differences between various theoretical models. When the strangeness content of the nucleon is neglected, these ratios can be extracted at leading order as

\[
\frac{\Delta u + \Delta \bar{u}}{u + \bar{u}} = \frac{4}{15} \frac{g_1^p}{F_1} \left( 4 + R_{du} \right) - \frac{1}{15} \frac{g_1^n}{F_1} \left( 1 + 4R_{du} \right) \tag{5}
\]

\[
\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}} = -\frac{1}{15} \frac{g_1^p}{F_1} \left( 4 + R_{du} \right) + \frac{4}{15} \frac{g_1^n}{F_1} \left( 4 + R_{du} \right) \tag{6}
\]

where \(R_{du} = (d + \bar{d})/(u + \bar{u})\) and is taken from the CJ12 parameterization [48]; \(g_1^n/F_1\) was modeled with world data [34,51,52,57,59] in the same way as \(g_1^p\). Measurements of \(g_1^n/F_1\) were not included in the fit so as not to introduce a model dependence in the choice of \(F_1\). An uncertainty of \(< 0.009\) for \((\Delta u + \Delta \bar{u})/(u + \bar{u})\) and \(< 0.02\) for \((\Delta d + \Delta \bar{d})/(d + \bar{d})\) was attributed to the neglect of systematic uncertainties. The difference in the result from varying each input within its uncertainty. Our results are given in Table 3, and plotted in Fig. 3 along with previous world DIS data and selected model predictions and parameterizations. The \((\Delta u + \Delta \bar{u})/(u + \bar{u})\) results, shown here for reference, are dominated by proton measurements. The semi-inclusive DIS ratios from HERMES [60] and COMPASS [61] are constructed from the published polarized PDFs, using the same unpolarized PDF parameterizations that were applied in the original analyses: CTEQ5L [62] in the case of the HERMES data, and MRST 2006 [63] for the COMPASS data. The uncertainties are therefore slightly larger than could be achieved from the raw data.

Two dedicated DIS \(A^1_n\) experiments [64,65] have been approved to run at Jefferson Lab in the coming years; one will use an
Table 3

(\Delta u + \Delta \bar{u})/(u + \bar{u}) and (\Delta d + \Delta \bar{d})/(d + \bar{d}) results. The reported systematic uncertainties include those from all sources, including the fit to world proton data, the parameterization of R^{0,4}, and neglect of the strangeness contribution.

<table>
<thead>
<tr>
<th>x</th>
<th>(\Delta u + \Delta \bar{u})/(u + \bar{u})</th>
<th>(\Delta d + \Delta \bar{d})/(d + \bar{d})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.277</td>
<td>0.423 ± 0.011 ± 0.031</td>
<td>-0.160 ± 0.094 ± 0.028</td>
</tr>
<tr>
<td>0.325</td>
<td>0.484 ± 0.006 ± 0.037</td>
<td>-0.283 ± 0.055 ± 0.032</td>
</tr>
<tr>
<td>0.374</td>
<td>0.515 ± 0.005 ± 0.044</td>
<td>-0.241 ± 0.048 ± 0.039</td>
</tr>
<tr>
<td>0.424</td>
<td>0.569 ± 0.005 ± 0.051</td>
<td>-0.499 ± 0.054 ± 0.051</td>
</tr>
<tr>
<td>0.474</td>
<td>0.595 ± 0.006 ± 0.063</td>
<td>-0.559 ± 0.070 ± 0.070</td>
</tr>
<tr>
<td>0.548</td>
<td>0.598 ± 0.009 ± 0.077</td>
<td>-0.356 ± 0.014 ± 0.097</td>
</tr>
</tbody>
</table>

open-geometry spectrometer [64]. These experiments will push to higher x, achieving greater sensitivity via improved targets and particle identification, and will test the assumption of Q^2 independence over a broad kinematic range; such tests are necessary because A^\perp_{2,3} measurements begin to probe quark OAM and higher-twist effects.

Our results for A^\perp_{2,3} and (\Delta d + \Delta \bar{d})/(d + \bar{d}) support previous measurements in the range 0.277 ≤ x ≤ 0.548. The A^\perp_{2,3} data are consistent with a zero crossing between x = 0.4 and x = 0.55, as reported by the Jefferson Lab E99-117 measurement [56]. Our data disfavor the original LSS (RBS) pQCD parameterization [14], while they do not show any extension that explicitly includes quark OAM [15]. Our leading-order extraction of (\Delta d + \Delta \bar{d})/(d + \bar{d}) shows no evidence of a transition to a positive slope, as is eventually required by hadron helicity conservation, in the x range probed. It is not yet possible to definitively distinguish between modern models – pQCD, statistical, NJL, or DSE – in the world data to date, but our data points will help constrain further work in the high-x regime. Our results were obtained with a new measurement technique, relying on an open-geometry spectrometer deployed at a large scattering angle with a gas Čerenkov detector to limit the charged-pion background.

Our data, in combination with previous measurements, suggest that additional neutron DIS measurements in the region 0.5 ≤ x ≤ 0.8 will be of particular interest in establishing the high-x behavior of the nucleon spin structure; in addition, an extension of the DSE-based approach [20] to x < 1 would be valuable. It is our hope that our data will inspire further theoretical work in the high-x DIS region.

Acknowledgements

We gratefully acknowledge the outstanding support of the Jefferson Lab Accelerator Division and Hall A staff in bringing this experiment to a successful conclusion. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Numbers DE-FG02-87ER40315 and DE-FG02-94ER40844 and Contract DE-AC05-06 OR 21.177, under which the Jefferson Science Associates, LLC, operate Jefferson Lab.

References

[38] Y.S. Tsai, Radiative corrections to electron scattering, SLAC-PUB-0848, 1971.