The Spin Structure of the Nucleon in the Valence Quark Region

Prepared by X. Zheng, J. P. Chen, and Z.-E. Meziani for the DNP web page

During a recent experiment at Thomas Jefferson National Accelerator Facility (Jefferson Lab, or JLab), precision data have been obtained, for the first time, on the spin structure of the neutron in the valence quark region. Such data provide an important test of our fundamental understanding of the nucleon structure and the spin/flavor features of the strong interaction. In particular, they suggest the importance of the quark orbital angular momentum in the nucleon spin.

The spin structure of the nucleon has been studied for over thirty years (for a review, see *e.g.* Adv. Nucl. Phys. **26**, 1 (2001)). The first set of data on the proton polarized structure functions from CERN in the late 1980's, combined with earlier data from SLAC, showed that only (12±17)% of the nucleon spin could be attributed to the quark spin. This result contradicted the valence quark model expectation, in which about 75% of the nucleon spin arises from the spin of the three valence quarks. Since the quark model is so successful as a qualitative guide to hadronic study, this observation was so surprising that it was named "*the proton spin crisis*" -- Where does the rest of the proton spin come from? Decades of effort have now been spent on making precision measurements to help us understand the origin of the nucleon's spin. The widely accepted interpretation is that the nucleon spin comes from the quark spin, the orbital angular momentum (OAM) of quarks, and the total angular momentum of gluons, with only (20-30)% from quark spin. Unfortunately, there have only been scant data on the quark OAM, and only a little information on the gluon polarization from indirect measurements. On the other hand, the valence quark model prediction could still hold, if each flavor of sea quark is moderately polarized in the opposite direction of the nucleon spin (Phys. Rev. D **59**, 034013 (1999)). However, this supposition has not been verified yet.

One clean region to test our understanding of the nucleon spin is the large x region. Here x is the Bjorken variable which describes the fraction of the nucleon momentum carried by a particular parton in the infinite momentum frame. In the large *x* region, valence quarks dominate (the large *x* region is also called "the valence quark region") and one may cleanly test whether the valence quark model is valid. Moreover, at long distances relative to the nucleon size, the theory of the strong interaction -- quantum chromo-dynamics (QCD) -- is highly non-perturbative, which makes the study of nucleon structure very difficult. But at very high *x,* one is supposed to reach the perturbative regime of QCD (Phys. Rev. Lett. **35**, 1416 (1975)). In this region, there are predictions of the quark spin based on the assumption that the OAM of the quarks is negligible (called leading-order pQCD or hadron helicity conservation).

In both the valence quark model and leading-order pQCD, the virtual photon asymmetry A_1, which is approximately the ratio of the polarized and unpolarized structure functions of the nucleon, will approach unity as $x \to 1$ for both the proton and the neutron. However, the data in the region of $x>0.4$ are very difficult to measure because the parton densities drop dramatically as *x* increases. Thus the cross section is very small and, even with high luminosity, a significant amount of time is needed to obtain good statistical precision. Existing data on A_1^n in the region $x>0.4$ all have large uncertainties and are even consistent with the predictions from naive spin-flavor SU(6) symmetry that $A_1^p=5/9$ and $A_1^n=0$. As for the $x \to 1$ behavior of polarized quark distributions, predictions from the two models are different. In leading-order pQCD, the quark (either the up or the down quark) which carries a majority of the nucleon's energy should have its spin aligned parallel to the nucleon spin, while in the valence quark model, the down quark carrying most of the nucleon's energy has its spin on average anti-aligned to the nucleon spin. The most recent quark polarization data from flavor-tagging semi-inclusive experiments performed by the HERMES collaboration are mostly in the low *x* region and cannot justify or refute either prediction.

During a recent experiment (E99117) led by Jian-Ping Chen of JLab and Zein-Eddine Meziani of Temple University, the JLab polarized continuous-wave electron beam impinged upon the Hall A polarized ^{3}He target (effectively a polarized neutron target), and precision deep inelastic scattering data on the neutron were collected in the valence quark region *x*>0.4 for the first time. The new results (X. Zheng *et al.*, the JLab Hall A Collaboration, Phys. Rev. Lett. 92, 012004 (2004)) unambiguously show that A_1^n turns positive at high *x* (see figure 1 below). The *x*-dependence of the new results suggests that A_1^n might reach unity at very high *x*. In general the trend agrees better with the valence quark model than with the leading-order pQCD predictions.

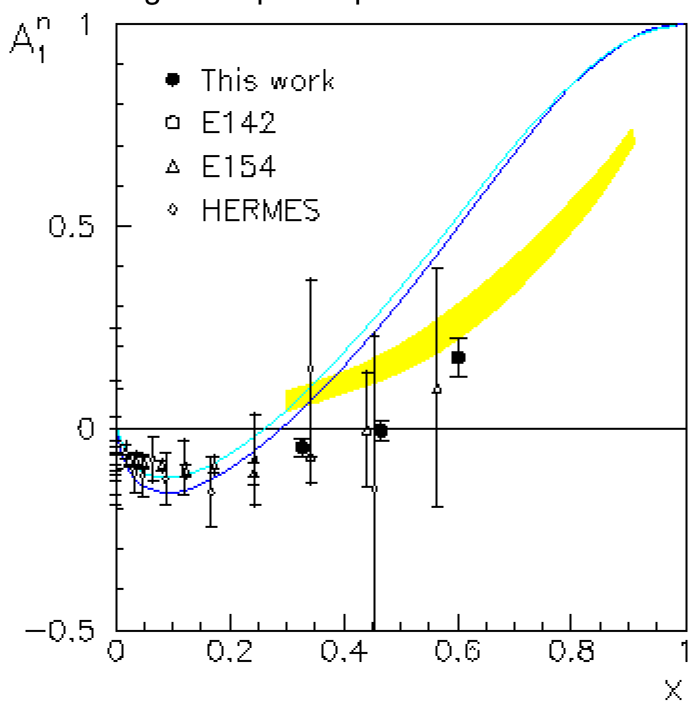

Figure 1: New results from JLab E99117 along with previous data from SLAC. The solid line at A_1^n=0 shows the spin-flavor SU(6) symmetry prediction. The curves are predictions from relativistic valence quark model (yellow band), BBS (blue) and LSS(BBS) parameterizations (cyan) based on leading-order pQCD. There exist predictions from various other models (see X. Zheng *et al.* PRL for details).

Combined with world proton data, polarized parton distribution functions were extracted for the up and the down quarks based on the quark parton model. While results for the up quark agree with most of the available calculations, results on the down quark agree with valence quark model predictions but disagree with that from leading-order pQCD (see figure 2 below). This implies that effects beyond the leading -order, such as quark OAM, may play an important role in the kinematic region explored by this experiment. This result is consistent with previous spin experiments in that it indicates that the quark OAM contributes significantly to the nucleon spin and should not be neglected even in the high-energy valence quark region. It also agrees with previous findings on the importance of quark OAM (Phys. Rev. C **65**, 065205 (2002), Phys. Rev. Lett. **91**, 092003 (2003) and Nucl. Phys. B **652**, 383 (2003)) from data on proton form factors, neutral pion photo-production, the ratio of N->Delta transition amplitudes E2/M1 and the tensor polarization in elastic e-^{2}H scattering.

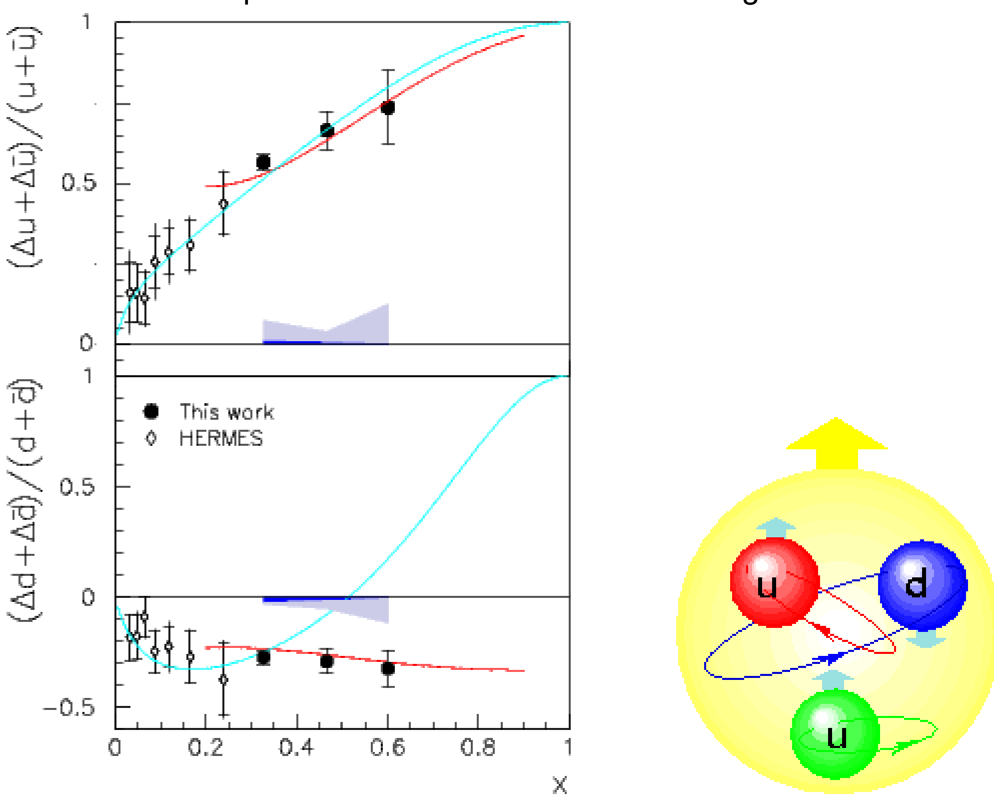

Figure 2: Polarized quark distributions as extracted from JLab E99117 data, along with data from HERMES and predictions from the relativistic valence quark model (red) and LSS(BBS) parameterizations (cyan) based on leading-order pQCD. The blue colored bands indicate the systematic uncertainties of the data. Please see X. Zheng *et al.* PRL for more details. The new results can be visualized by the cartoon on the right -- when either of the two up valence quarks is probed, its spin (light-blue arrow) is found to be aligned to the nucleon spin (yellow arrow), but when the down valence quark is probed, its spin is found to be anti-aligned to the nucleon spin. These results reveal the important role played by the valence quark OAM (thin elliptics) in forming the nucleon spin.

The precision data from JLab provide the first clean test of models for the nucleon spin in the valence quark region, and provide crucial input to QCD fits to parton distributions. The results are consistent with the present valence quark picture and have indicated the importance of quark orbital angular momentum in the valence quark region. The new results have helped physicists to proceed one step closer to a resolution of the proton spin crisis.