Novel Nuclear Effects in QCD: The Non-Universality of Nuclear Antishadowing and the Implications of Hidden Color

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Abstract. The shadowing and antishadowing of nuclear structure functions in the Gribov-Glauber picture is due to the destructive and constructive interference of amplitudes arising from the multiple-scattering of quarks in the nucleus, respectively. The diffractive contributions to deep inelastic scattering includes Pomeron and Odderon contributions from multi-gluon exchange as well as Reggeon quark-exchange contributions. The coherence of multi-step nuclear processes leads to shadowing and antishadowing of the electromagnetic nuclear structure functions in agreement with measurements. This picture also leads to substantially different antishadowing for charged and neutral current reactions, thus affecting the extraction of the weak-mixing angle θ_W. The fact that Reggeon couplings depend on the quantum numbers of the struck quark implies non-universality of nuclear antishadowing for charged and neutral currents as well as a dependence of antishadowing on the polarization of the beam and target. The implications of hidden color degrees of freedom in the nuclear wavefunction is also briefly discussed.

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ANTISHADOWING OF NUCLEAR STRUCTURE FUNCTIONS

One of the novel features of QCD involving nuclei is the *antishadowing* of the nuclear structure functions which is observed in deep inelastic lepton scattering and other hard processes. Empirically, one finds $R_A(x,Q^2) \equiv \big(F_{2A}(x,Q^2)/(A/2)F_d(x,Q^2)\big) > 1$ in the domain $0.1 < x < 0.2$; *i.e.*, the measured nuclear structure function (referenced to the deuteron) is larger than than the scattering on a set of A independent nucleons. For many years the only theoretical guidance to this phenomenon was that given by Nikolaev and Zakharov [1], who argued that antishadowing was needed to restore the momentum sum rule in nuclei, compensating the shadowing and EMC regimes. However, this argument does not explain the dynamical mechanism which creates antishadowing nor the location in x_{bj} where it occurs.

The shadowing of the nuclear structure functions: $R_A(x,Q^2) < 1$ at small $x < 0.1$ can be readily understood in terms of the Gribov-Glauber theory. Consider the two-step process illustrated in Fig. 1 in the nuclear target rest frame. The incoming $q\overline{q}$ dipole first interacts diffractively $\gamma^* N_1 \to (q\overline{q})N_1$ on nucleon N_1 leaving it intact. This is the leading-twist diffractive deep inelastic scattering (DDIS) process which has been measured at HERA to constitute approximately 10% of the DIS cross section at high energies. The $q\overline{q}$ state then interacts inelastically on a downstream nucleon $N_2 : (q\overline{q})N_2 \to X$. The phase of the pomeron-dominated DDIS amplitude is close to imaginary, and the

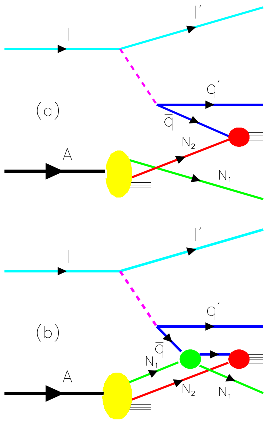

FIGURE 1. Illustration of one-step and two-step processes.

Glauber cut provides another phase i, so that the two-step process has opposite phase and destructively interferes with the one-step DIS process $\gamma * N_2 \to X$ where N_1 acts as an unscattered spectator. The one-step and-two step amplitudes can coherently interfere as long as the momentum transfer to the nucleon N_1 is sufficiently small that it remains in the nuclear target; *i.e.*, the Ioffe length [2] $L_I = 2M\nu/Q^2$ is large compared to the inter-nucleon separation. In effect, the flux reaching the interior nucleons is diminished, thus reducing the number of effective nucleons and $R_A(x,Q^2) < 1$.

As noted by Hung Jung Lu and myself [3], there are also leading-twist diffractive contributions $\gamma^* N_1 \to (q\bar{q})N_1$ arising from Reggeon exchanges in the t-channel. For example, isospin–non-singlet $C = +$ Reggeons contribute to the difference of proton and neutron structure functions, giving the characteristic Kuti-Weisskopf $F_{2p} - F_{2n} \sim x^{1-\alpha_R(0)} \sim x^{0.5}$ behavior at small x. The x dependence of the structure functions reflects the Regge behavior $\nu^{\alpha_R(0)}$ of the virtual Compton amplitude at fixed Q^2 and $t = 0$. The phase of the diffractive amplitude is determined by analyticity and crossing to be proportional to $-1+i$ for $\alpha_R = 0.5$, which together with the phase from the Glauber cut, leads to *constructive* interference of the diffractive and nondiffractive multi-step nuclear amplitudes. Furthermore, because of its x dependence, the nuclear structure function is enhanced precisely in the domain $0.1 < x < 0.2$ where antishadowing is empirically observed. The strength of the Reggeon amplitudes is fixed by the fits to the nucleon structure functions, so there is little model dependence.

The origin of the diffractive contributions to DIS was shown in Ref. [4] to be due to the rescattering of the struck quark after it is struck in the usual parton model frame $q^+ \leq 0$, an effect induced by the Wilson line connecting the currents. Thus one cannot attribute DDIS to the physics of the target nucleon computed in isolation. It is an effect resulting from the $\gamma^* p$ collision. Similarly, since shadowing and antishadowing arise from the physics of diffraction, we cannot attribute these phenomena to the structure of the nucleus itself: shadowing and antishadowing arise because of the $\gamma^* A$ collision and the history of the $q\bar{q}$ dipole as it propagates through the nucleus.

In a recent paper, Ivan Schmidt, Jian-Jun Yang, and I [5] have extended this analysis to the shadowing and antishadowing of all of the electroweak structure functions. Quarks

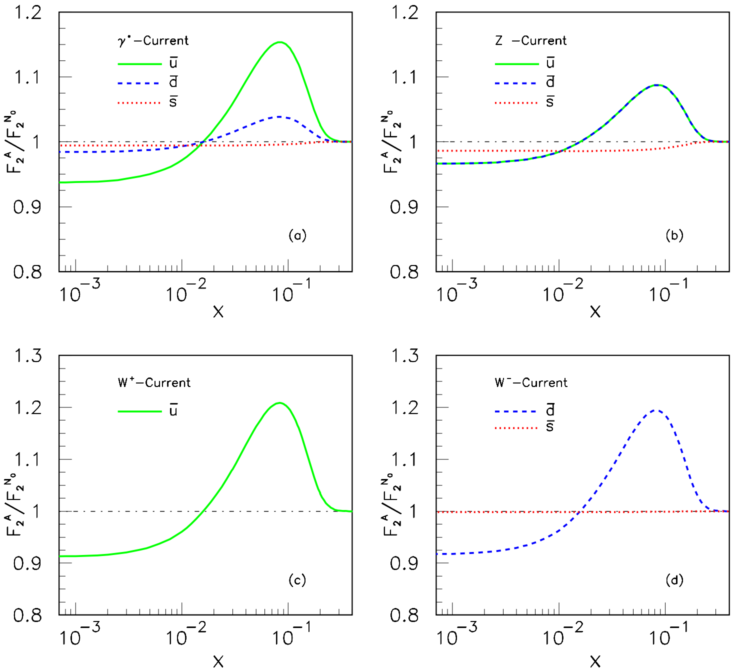

FIGURE 2. Model predictions [5] for interactions of electroweak interactions on antiquarks in nuclear targets. The antishadowing effect is not as large for quark currents.

of different flavors will couple to different Reggeons; this leads to the remarkable prediction that nuclear antishadowing is not universal; it depends on the quantum numbers of the struck quark. This picture leads to substantially different antishadowing for charged and neutral current reactions, thus affecting the extraction of the weak-mixing angle θ_W. See Fig. 2. We find that part of the anomalous NuTeV result [6] for θ_W could be due to the nonuniversality of nuclear antishadowing for charged and neutral currents. Detailed measurements of the nuclear dependence of individual quark structure functions are thus needed to establish the distinctive phenomenology of shadowing and antishadowing and to make the NuTeV results definitive. Schmidt, Yang, and I have also identified contributions to the nuclear multi-step reactions which arise from odderon exchange and also hidden color degrees of freedom in the nuclear wavefunction. There are other ways in which this new view of antishadowing can be tested; antishadowing can also depend on the target and beam polarization.

HIDDEN COLOR

One of the most important distinctions between traditional nuclear physics and QCD descriptions of nuclei are the hidden color degrees of freedom of the nuclear wavefunction [7]. For example, there are five color-singlet combinations of six color-triplet quarks in the deuteron valence Fock state: $3_C \times 3_C \times 3_C \times 3_C \times 3_C \times 3_C = 1_C + 1_C + 1_C + 1_C + 1_C + \cdots$, only one of which is identified with the $n-p$ degrees of freedom at large distances. At short distances the 5-component deuteron distribution amplitude

$\phi(x_i,Q)_I$ evolves at $Q^2 \gg \Lambda^2_{QCD}$ until at asymptotic momenta all five components have equal weight. The asymptotic large-momentum-transfer behavior of the deuteron form factor and the form of the deuteron distribution amplitude at short distances can be rigorously derived from perturbative QCD. The fact that the six-quark state is 80% hidden color at small transverse separation implies that the deuteron form factors cannot be described at large Q^2 by meson-nucleon degrees of freedom, and that the nucleon-nucleon potential is repulsive at short distances.

The observed $Q^{10}F_d(Q^2)$ scaling of the helicity-conserving deuteron form factor [8] and the fixed CM angle scaling of the deuteron photodisintegration cross section [9] $s^{11}\frac{d\sigma}{dt}(\gamma d \to np) = F(t/s)$ provide remarkable tests of the conformal properties of QCD at short distances in a nuclear system as predicted by QCD and the AdS/CFT correspondence. The measured reduced form factor of the deuteron [10] $f_d(Q^2) \equiv F_d(Q^2)/F_N^2(Q^2/4)$ falls quickly at small $Q^2R_d^2 < 1$, and then scales as the pion monopole form factor: $f_d(Q^2) \sim 0.15 \times F_\pi(Q^2)$ at $Q^2 >> 1$ GeV^2, suggesting that the hidden color degrees of freedom dominate the deuteron wavefunction at high momentum transfer $k_\perp^2 > 1$ GeV^2 with an approximate normalization of 15%.

The hidden color $(uud)_{8C}(duu)_{8C}$ Fock states of the deuteron have a sizable overlap with the $\Delta^{++}(uuu)\Delta^-(ddd)$ di-isobar state. Thus one expects from QCD hidden color that the $\frac{d\sigma}{dt}(\gamma d \to \Delta^{++}\Delta^-)$ and $\frac{d\sigma}{dt}(\gamma d \to np)$ cross sections become comparable in the fixed angle scaling regime.

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REFERENCES

1. N. N. Nikolaev and V. I. Zakharov, Phys. Lett. B **55**, 397 (1975).
2. B. L. Ioffe, Phys. Lett. B **30**, 123 (1969).
3. S. J. Brodsky and H. J. Lu, Phys. Rev. Lett. **64**, 1342 (1990).
4. S. J. Brodsky, P. Hoyer, N. Marchal, S. Peigne and F. Sannino, Phys. Rev. D **65**, 114025 (2002) [arXiv:hep-ph/0104291].
5. S. J. Brodsky, I. Schmidt and J. J. Yang, Phys. Rev. D **70**, 116003 (2004) [arXiv:hep-ph/0409279].
6. G. P. Zeller *et al.* [NuTeV Collaboration], Phys. Rev. Lett. **88**, 091802 (2002) [Erratum-ibid. **90**, 239902 (2003)] [arXiv:hep-ex/0110059].
7. S. J. Brodsky, C. R. Ji and G. P. Lepage, Phys. Rev. Lett. **51**, 83 (1983).
8. R. J. Holt, Phys. Rev. C **41**, 2400 (1990).
9. P. Rossi *et al.* [CLAS Collaboration], arXiv:hep-ph/0405207.
10. S. J. Brodsky and B. T. Chertok, Phys. Rev. D **14**, 3003 (1976).