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New Directions in QCD and The Electron-Ion Collider [*]

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Electron-proton collisions have historically provided the most detailed constraints on the fundamental constituent structure of hadrons and nuclei, as well as testing fundamental aspects of quantum chromodynamics. Many QCD phenomena have been discovered or confirmed in electroproduction, including DGLAP evolution, duality, spin anomalies, leading-twist diffraction, color transparency, nuclear shadowing and anti-shadowing, the scaling behavior of hard exclusive hadron and nuclear reactions, jet hadronization, and hard pomeron phenomena. The electroproduction field has now been extended to many new areas, particularly diffractive phenomena, single-spin asymmetries, semi-exclusive reactions, and deeply virtual Compton scattering.

Although there has been great progress in understanding the quark and gluon structure of proton and nuclei, many fundamental questions concerning QCD remain, such as hadronization at the amplitude level, the nature of the running coupling and masses at low scales, the division of the proton's angular momentum among its constituents, the role of hidden-color degrees of freedom in nuclei, distinguishing renormalon-induced versus dynamical higher twist effects, the intrinsic heavy-quark structure of hadron wavefunctions, quark-antiquark asymmetries, single-spin asymmetries and spin-spin correlations, anomalously large heavy quark production cross sections, heavy-quark threshold effects, the observed breaking of gauge-coherent color transparency [1], the origin of nuclear shadowing and anti-shadowing, and the physics of leading-twist diffraction, including hard and soft pomeron and odderon phenomena. An electron-ion collider [2] with proton and electron polarization capabilities will greatly illuminate these questions.[3].

Light-front wavefunctions provide an intuitive but rigorous representation of the nonperturbative QCD structure of hadrons at the amplitude level [4]. In principle, the light-front wavefunctions of hadrons can be computed by diagonalizing the QCD Hamiltonian H_{LF} quantized at fixed $\tau = t + z/c$ in light-cone gauge $A^+ = 0$. The $n-$particle Fock state wavefunctions $\psi_n(x_i, k_{i,\perp,}\lambda_i)$ are then obtained as the projections of the hadron's eigenstate on the free particle Fock basis. Remarkably, the light-front wavefunctions are independent of the hadron's total momentum, and each Fock state component satisfies J_z conservation and gives vanishing anomalous gravitomagnetic moment [5].

Given the light-front wavefunctions amplitudes, one can calculate many hadronic processes measured in ep collisions from first principles. The sum of squares of the light-front wavefunctions give the quark and gluon distributions including all spin measures and correlations. Form factors and exclusive weak decay matrix elements have exact representations as overlap integrals of the light-front wavefunctions. The proton anomalous moment is computed an overlap of light-front wavefunctions differing by one unit of orbital angular momentum $\Delta L_z = 1$. Similarly, the deeply virtual Compton amplitude $\gamma p \to \gamma p'$ can be expressed as overlap integrals $n = n', n = n' + 2$ of the initial and final light-front proton wavefunctions [6, 7]. The hadron distribution amplitudes $\phi^H(x_i, Q)$ which control hard exclusive processes [8], including form factors, exclusive electroproduction, semi-exclusive reactions [9] and exclusive B decays are computed from the transverse momentum integrals of the lowest particle number Fock state wavefunction. Similarly, the physics of diffractive electroproduction $\gamma^* p \to V^0 p$ can be understood as a convolution of the photon's light-front wavefunctions with vector meson distribution amplitudes [11]. The nonperturbative aspects of the light-front wavefunctions of real and virtual photons can be measured directly in nuclear diffractive dissociation processes $\gamma^* A \to q\bar{q}A$. The proton's light-front wavefunction can be resolved into three jets by Coulomb dissociation in $pe \to qqqe$. Similarly, nuclear light-front wavefunctions can be resolved into their meson and nucleon components via Coulomb dissociation.

Recently, Hoyer, Marchal, Peigne, and Sannino and I [10] have challenged the conventional view that the structure functions measured in deep inelastic lepton scattering are simply the probability distributions for finding quarks and gluons in the target as computed from the square of light-front wavefunctions. We show that this is in fact not actually correct in gauge theory. Gluon exchange between the fast, outgoing partons and the target spectators, which is usually assumed to be an irrelevant gauge artifact, actually affects the leading-twist structure functions in a profound way. This observation removes the apparent contradiction between the projectile (eikonal) and target (parton model) views of diffractive and small $x_{\rm Bjorken}$ phenomena. The diffractive scattering of the fast outgoing quarks on spectators in the target in turn causes shadowing in the DIS cross section. Thus the depletion of the nuclear structure functions is not intrinsic to the wave function of the nucleus, but is a coherent effect arising from the destructive interference of diffractive channels induced by final-state interactions. This is consistent with the Glauber-Gribov interpretation of shadowing as a rescattering effect. Similarly, the effective pomeron distribution in the proton is not derived from its light-front wavefunction.

Measurements from the HERMES and SMC collaborations show a remarkably large single-spin asymmetry in semi-inclusive pion leptoproduction $\gamma^*(q)p \to \pi X$ when the proton is polarized normal to the photon-to-pion production plane. Recently, Hwang, Schmidt, and I [12] have shown that final-state interactions from gluon exchange between the outgoing quark and the target spectator system lead to single-spin asymmetries in deep inelastic lepton-proton scattering at leading twist in perturbative QCD; *i.e.*, the rescattering corrections are not power-law suppressed at large photon virtuality Q^2 at fixed x_{bj}. The existence of such single-spin asymmetries requires a phase difference between two amplitudes coupling the proton target with $J^z_p = \pm\frac{1}{2}$ to the same final-state, the same amplitudes which are necessary to produce a nonzero proton anomalous magnetic moment. We show that the exchange of gauge particles between the outgoing quark and the proton spectators produces a Coulomb-like phase which depends on the angular momentum L^z of the proton's constituents and is thus distinct for different proton spin amplitudes. The single-spin asymmetry which arises from such final-state interactions does not factorize into a product of distribution function and fragmentation function, and it is not related to the transversity distribution $\delta q(x,Q)$ which correlates transversely polarized quarks with the spin of the transversely polarized target nucleon. These effects highlight the unexpected importance of final- and initial-state interactions in QCD observables – they lead to leading-twist single-spin asymmetries, diffraction, and nuclear shadowing, phenomena not included in the wavefunction of the target. Final-state interactions and intrinsic heavy quark distributions also play an important role in charm and bottom electroproduction at threshold [13].

The probability of heavy quark Fock states in the proton rigorously scales as $1/m_Q^2$ [14], which is a unique feature of non-Abelian theory. Gardner and I have shown that the presence of intrinsic charm in the $B-$meson light-front wave function, even at a few percent level, provides new, competitive decay mechanisms for B decays which are nominally CKM-suppressed [15]. It is thus important to test intrinsic heavy quark phenomena by measuring the charm and bottom structure functions at large x_{bj} and by measuring the strength of leading charm effects in the proton fragmentation region. In addition, one can detect the QCD odderon and measure the interference of odderon and pomeron exchange by observing the asymmetry of the momentum distributions in leading charm and anti-charm production [16].

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