Hard Diffraction in QCD

Stanley J. Brodsky

Stanford Linear Accelerator Center, Stanford University, Stanford, CA, 94309

Abstract. Gluon exchange between the outgoing quarks and the target spectators affects the structure functions measured in deep inelastic scattering in a profound way, leading to diffractive leptoproduction processes, the shadowing and antishadowing of nuclear structure functions, and target spin asymmetries – leading-twist physics not incorporated in the light-front wavefunctions of the target computed in isolation. I also discuss the diffraction dissociation of hadrons into jets as a tool for resolving fundamental hadron substructure.

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DIFFRACTIVE DEEP INELASTIC SCATTERING

A remarkable feature of deep inelastic lepton-proton scattering at HERA is that approximately 10% events are diffractive [1, 2]: the target proton remains intact, and there is a large rapidity gap between the proton and the other hadrons in the final state. These diffractive deep inelastic scattering (DDIS) events can be understood most simply from the perspective of the color-dipole model: the $q\overline{q}$ Fock state of the high-energy virtual photon diffractively dissociates into a diffractive dijet system. The exchange of multiple gluons between the color dipole of the $q\overline{q}$ and the quarks of the target proton neutralizes the color separation and leads to the diffractive final state. The same multiple gluon exchange also controls diffractive vector meson electroproduction at large photon virtuality [3]. This observation presents a paradox: if one chooses the conventional parton model frame where the photon light-front momentum is negative $q+ = q^0 + q^z < 0$, the virtual photon interacts with a quark constituent with light-cone momentum fraction $x = k^+/p^+ = x_{bj}$. If one chooses light-cone gauge $A^+ = 0$, then the gauge link associated with the struck quark (the Wilson line) becomes unity. Thus the struck “current" quark experiences no final-state interactions. Since the light-front wavefunctions $\psi_n(x_i, k_{\perp i}$ of a stable hadron are real, it appears impossible to generate the required imaginary phase associated with pomeron exchange, let alone large rapidity gaps.

This paradox was resolved by Paul Hoyer, Nils Marchal, Stephane Peigne, Francesco Sannino and myself [4]. Consider the case where the virtual photon interacts with a strange quark – the $s\overline{s}$ pair is assumed to be produced in the target by gluon splitting. In the case of Feynman gauge, the struck s quark continues to interact in the final state via gluon exchange as described by the Wilson line. The final-state interactions occur at a light-cone time $\Delta\tau \simeq 1/\nu$ shortly after the virtual photon interacts with the struck quark. When one integrates over the nearly-on-shell intermediate state, the amplitude acquires an imaginary part. Thus the rescattering of the quark produces a separated color-singlet $s\overline{s}$ and an imaginary phase. In the case of the light-cone gauge $A^+ = \eta \cdot A = 0$, one must also consider the final-state interactions of the (unstruck) $\bar{s}$ quark. The gluon propagator in light-cone gauge $d_{LC}^{\mu\nu}(k) = (i/k^2 + i\varepsilon)\left[-g^{\mu\nu} + (\eta^{\mu}k^{\nu} + k^{\mu}\eta^{\nu}/\eta\cdot k)\right]$ is singular at $k^+ = \eta\cdot k = 0$. The momentum of the exchanged gluon k^+ is of $\mathscr{O}(1/\nu)$; thus rescattering contributes at leading twist even in light-cone gauge. The net result is gauge invariant and is identical to the color dipole model calculation. The calculation of the rescattering effects on DIS in Feynman and light-cone gauge through three loops is given in detail for an Abelian model in Ref. [4]. The result shows that the rescattering corrections reduce the magnitude of the DIS cross section in analogy to nuclear shadowing.

A new understanding of the role of final-state interactions in deep inelastic scattering has thus emerged. The multiple scattering of the struck parton via instantaneous interactions in the target generates dominantly imaginary diffractive amplitudes, giving rise to an effective “hard pomeron" exchange. The presence of a rapidity gap between the target and diffractive system requires that the target remnant emerges in a color-singlet state; this is made possible in any gauge by the soft rescattering. The resulting diffractive contributions leave the target intact and do not resolve its quark structure; thus there are contributions to the DIS structure functions which cannot be interpreted as parton probabilities [4]; the leading-twist contribution to DIS from rescattering of a quark in the target is a coherent effect which is not included in the light-front wave functions computed in isolation. One can augment the light-front wave functions with a gauge link corresponding to an external field created by the virtual photon $q\bar{q}$ pair current [5, 6]. Such a gauge link is process dependent [7], so the resulting augmented LFWFs are not universal [4, 5, 8]. We also note that the shadowing of nuclear structure functions is due to the destructive interference between multi-nucleon amplitudes involving diffractive DIS and on-shell intermediate states with a complex phase. In contrast, the wave function of a stable target is strictly real since it does not have on-energy-shell intermediate state configurations. The physics of rescattering and shadowing is thus not included in the nuclear light-front wave functions, and a probabilistic interpretation of the nuclear DIS cross section is precluded.

Rikard Enberg, Paul Hoyer, Gunnar Ingelman and I [9]. have shown that the quark structure function of the effective hard pomeron has the same form as the quark contribution of the gluon structure function. The hard pomeron is not an intrinsic part of the proton; rather it must be considered as a dynamical effect of the lepton-proton interaction. Our QCD-based picture also applies to diffraction in hadron-initiated processes. The rescattering is different in virtual photon- and hadron-induced processes due to the different color environment, which accounts for the observed non-universality of diffractive parton distributions. This framework also provides a theoretical basis for the phenomenologically successful Soft Color Interaction (SCI) model [10] which includes rescattering effects and thus generates a variety of final states with rapidity gaps.

SINGLE-SPIN ASYMMETRIES FROM FINAL-STATE INTERACTIONS

Among the most interesting polarization effects are single-spin azimuthal asymmetries in semi-inclusive deep inelastic scattering, representing the correlation of the spin of the proton target and the virtual photon to hadron production plane: $\vec{S}_p \cdot \vec{q} \times \vec{p}_H$. Such asymmetries are time-reversal odd, but they can arise in QCD through phase differences in different spin amplitudes. In fact, final-state interactions from gluon exchange between the outgoing quarks and the target spectator system lead to single-spin asymmetries in semi-inclusive deep inelastic lepton-proton scattering which are not power-law suppressed at large photon virtuality Q^2 at fixed x_{bj} [11] In contrast to the SSAs arising from transversity and the Collins fragmentation function, the fragmentation of the quark into hadrons is not necessary; one predicts a correlation with the production plane of the quark jet itself. Physically, the final-state interaction phase arises as the infrared-finite difference of QCD Coulomb phases for hadron wave functions with differing orbital angular momentum. The same proton matrix element which determines the spin-orbit correlation $\vec{S} \cdot \vec{L}$ also produces the anomalous magnetic moment of the proton, the Pauli form factor, and the generalized parton distribution E which is measured in deeply virtual Compton scattering. Thus the contribution of each quark current to the SSA is proportional to the contribution $\kappa_{q/p}$ of that quark to the proton target's anomalous magnetic moment $\kappa_p = \sum_q e_q \kappa_{q/p}$ [11, 12]. The HERMES collaboration has recently measured the SSA in pion electroproduction using transverse target polarization [13]. The Sivers and Collins effects can be separated using planar correlations; both contributions are observed to contribute, with values not in disagreement with theory expectations [13, 14] .

A related analysis also predicts that the initial-state interactions from gluon exchange between the incoming quark and the target spectator system lead to leading-twist single-spin asymmetries in the Drell-Yan process $H_1 H_2^{\updownarrow} \to \ell^+ \ell^- X$ [7, 15]. The SSA in the Drell-Yan process is the same as that obtained in SIDIS, with the appropriate identification of variables, but with the opposite sign. Initial-state interactions also lead to a $\cos 2\phi$ planar correlation in unpolarized Drell-Yan reactions [16]. There is no Sivers effect in charged-current reactions since the W only couples to left-handed quarks [17].

DIFFRACTION DISSOCIATION AS A TOOL TO RESOLVE HADRON SUBSTRUCTURE

Diffractive multi-jet production in heavy nuclei provides a novel way to resolve the shape of light-front Fock state wave functions and test color transparency [18]. For example, consider the reaction [19, 20] $\pi A \to \mathrm{Jet}_1 + \mathrm{Jet}_2 + A'$ at high energy where the nucleus A' is left intact in its ground state. The transverse momenta of the jets balance so that $\vec{k}_{\perp i} + \vec{k}_{\perp 2} = \vec{q}_\perp < R^{-1}{}_A$. Because of color transparency, the valence wave function of the pion with small impact separation will penetrate the nucleus with minimal interactions, diffracting into jet pairs [19]. The $x_1 = x$, $x_2 = 1 - x$ dependence of the di-jet distributions will thus reflect the shape of the pion valence light-cone wave function in x; similarly, the $\vec{k}_{\perp 1} - \vec{k}_{\perp 2}$ relative transverse momenta of the jets gives key information on the second transverse momentum derivative of the underlying shape of the valence pion wavefunction [20, 21]. The diffractive nuclear amplitude extrapolated to $t = 0$ should be linear in nuclear number A if color transparency is correct. The integrated diffractive rate will then scale as $A^2/R_A^2 \sim A^{4/3}$. This is in fact what has been observed by the E791 collaboration at FermiLab for 500 GeV incident pions on nuclear targets [22].

The measured momentum fraction distribution of the jets is found to be approximately consistent with the shape of the pion asymptotic distribution amplitude [23, 24, 25]. $\phi_\pi^{\text{asympt}}(x) = \sqrt{3} f_\pi x(1-x)$ [26]. The concept of high energy diffractive dissociation can be generalized to provide a tool to materialize the individual Fock states of a hadron, photon, or nuclear projectile; *e.g.*, the diffractive or Coulomb dissociation of a high energy proton $pA \to qqqA'$ or $pe \to qqqe$ can be used to measure the valence light-front wavefunction of the proton.

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