SLAC-PUB-7212
July 1996
( )

Nuclear Effects at HERA

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Abstract: The development of a nuclear beam facility at HERA would allow the study of fundamental features of quark and gluon interactions in QCD. I briefly review the physics underlying nuclear shadowing and anti-shadowing as well as other diffractive and jet fragmentation processes that can be studies in high energy electron-nucleus collisions.

Work supported by Department of Energy contract DE–AC03–76SF00515.

The use of nuclear targets and beams in high energy collisions provides a practical way to vary the external parameters of QCD. At HERA, one can employ nuclear beams to probe deep inelastic lepton scattering on nuclei in the small x regime where non-additive nuclear effects are large, reflecting the space-time propagation of quarks and gluons. One can also test other important nuclear effects, such as the energy loss of quarks propagating in nuclear matter, color transparency phenomena in coherent and quasielastic diffractive processes, and nuclear photoabsorption.

In the conventional infinite momentum frame parton model picture of DIS, the electron scatters on a quark constituent of the target. In the corresponding description in the nuclear rest frame, the incident transversely polarized virtual photon first splits into a pair $\gamma_T^* \to q\overline{q}$ and the anti-quark is absorbed in the target. The scattered quark then appears as a jet aligned with the incident virtual photon [1]. Thus from the laboratory frame perspective, the nuclear dependence of the transverse nuclear structure function $F^T(x,Q^2)_A$ directly reflects the nuclear dependence of the quark-nucleus cross section $\sigma_{qA}(\widehat{s})$ at a corresponding CM energy squared $\widehat{s} = \mathcal{O}(\overline{k}_\perp^2/x)$ [2]. Here $\overline{k}_\perp^2$ is the mean square transverse momentum of the interacting quark. At very small x the effective laboratory energies can reach 10^5 GeV, and thus the nuclear dependence of the transverse structure function reflects the Pomeron-like interactions of the quark, including its elastic and inelastic interactions within the nucleus. Thus one expects that the dominant quark interactions to occur on the front surface of the nucleus and $F^T(x,Q^2)_A < AF^T(x,Q^2)_N$ [3]. At moderate $x \sim 0.15$, the Reggeon contributions to the quark-nucleon scattering become important; because of their phase structure the multi-scattering amplitudes can lead to constructive interference, and thus to anti-shadowing; *i.e.* $F^T(x,Q^2)_A > AF^T(x,Q^2)_N$ [4]. For electron scattering on light nuclei, such as the deuteron, one can also generate non-additive contributions from the "hidden color" non-nucleon Fock components of the nucleus [5].

Examining the nuclear dependence of the final hadronic state is also illuminating. The hadronization and fragmentation of the jet which is produced aligned along the photon direction will reflect the energy loss mechanisms and multiple scattering of the quark as it propagates through the nucleus. On general quantum mechanical grounds, the high energy outgoing jet can only lose a finite amount of energy so that the fragmentation function still factorizes in leading twist—even though the quark transits the nucleus [6]. More recently, Baier *et al.* have argued that the energy loss can scale as the square of the nuclear length because of specific non-Abelian effects [7]. Bjorken has also discussed the predictions for rapidity gaps in deep inelastic electron-nucleus collisions [1].

In contrast, the leading-twist contribution to the longitudinal structure function $F^L(x, Q^2)_A$ derives from the interaction of a approximately symmetric $q\overline{q}$ component of the virtual photon wavefunction with relative impact separation $b_\perp \sim \mathcal{O}(1/Q)$. The specific nuclear effects at low x then reflect the interactions of a small-color singlet system, thus leading to decreasing nuclear absorption with increasing Q^2. Thus the study of shadowing as a function of photon polarization and Q^2 can illuminate the basic mechanisms underlying short-distance QCD processes.

It is also interesting to measure the shadowing of the charm and bottom cross section. The basic underlying subprocess at low x is photon-gluon fusion. Thus the nuclear dependence of the heavy quark structure functions measures the shadowing of the gluon distribution in the nucleus, which in turn reflects the shadowing of the gluon-nucleus cross section.

It is also very interesting to measure the nuclear dependence of totally diffractive vector meson production $d\sigma/dt(\gamma^* A \to VA)$ [8] at HERA energies. For large photon virtualities (or for heavy vector quarkonium), the small color dipole moment of the vector system implies minimal absorption; *i.e.*, color transparency. The interacting $q\overline{q}$ system stays small over the entire nuclear length at HERA energies. Thus, remarkably, QCD predicts that the forward amplitude $\gamma^* A \to VA$ at $t \to 0$ is nearly linear in A. One also is sensitive to corrections from the nonlinear A-dependence of the nearly forward matrix element that couples two gluons to the nucleus, which in turn reflects the square of the nuclear dependence of the gluon structure function of the nucleus [9]. Because of color transparency, the integral of the diffractive cross section over the forward peak is thus predicted to scale approximately $A^2/R_A^2 \sim A^{4/3}$. A test of this striking prediction could be carried out at very small $t_{\min}$ at HERA and would provide a striking test of QCD in exclusive nuclear reactions. Evidence for color transparency in quasi-elastic ρ leptoproduction $\gamma^* A \to \rho^0 N(A-1)$ has recently been reported by the E665 experiment [10] at Fermilab.

In QCD, the proton is represented at a given light-cone time $\tau = t + z$ as a superposition of quark and gluon Fock states $|uud>$, $|uudg>$, $|uudgg>$, $|uudQ\overline{Q}>$, etc. Thus when the proton is expanded on a free quark and gluon basis, it is a fluctuating system of arbitrarily large particle number. The light-cone wavefunctions $\psi_n(x_i, k_{\perp i}, \lambda_i)$ are the probability amplitudes which describe the projections of the proton state on this Hilbert space. The structure functions measured in deep inelastic lepton scattering are directly related to the light-cone x momentum distributions of the quarks and gluons determined by the $|\psi_n|^2$. An equally interesting measure of the proton's structure is to examine the system of hadrons produced in the proton's fragmentation region when one quark is removed; *i.e.*, the proton's "fracture functions". At HERA the particles derived from the spectator $\overline{3}_C$ system which are intrinsic to the proton's structure are produced in the proton beam direction with approximately the same rapidity as that of the proton at relatively small transverse momentum. Thus in high energy ep collisions, the electron resolves the diffractively-excited proton, revealing the correlations of the spectator quarks and gluons in its light cone Fock components with invariant mass extending up to the energy of the collision.

It is of particular interest to examine the fragmentation of the proton when the electron strikes a light quark and the interacting Fock component is the $|uudc\bar{c}>$ or $|uudb\bar{b}>$ state. These Fock components correspond to intrinsic charm or intrinsic bottom quarks in the proton wavefunction. Since the heavy quarks in the proton bound state have roughly the same rapidity as the proton itself, the intrinsic heavy quarks will appear at large x_F. One expects heavy quarkonium and also heavy hadrons to be formed from the coalescence of one (or more) heavy quarks with the valence u and d quarks, since they have nearly the same rapidity[11]. Since the heavy and valence quark momenta combine, these states are preferably produced with large longitudinal momentum fractions. A recent analysis by Harris, Smith and Vogt of the excessively large charm structure function of the proton at large x as measured by the EMC collaboration at CERN implies that the probability $P_{c\bar{c}}$ that the proton contains intrinsic charm Fock states is of the order of 0.6% [12]. In the case of intrinsic bottom, PQCD scaling predicts $P_{b\bar{b}} = P_{c\bar{c}} \frac{m_\psi^2}{m_\Upsilon^2} \frac{\alpha_s^4(m_b)}{\alpha_s^4(m_c)}$, more than an order of magnitude smaller. A discussion of the physics of intrinsic heavy quark states and the dependence of the resolution of intrinsic heavy particle Fock states on photon virtuality Q^2 is presented in Ref. [13].

It is also illuminating to study the target fragmentation region at HERA with nuclear targets [13]. The spectator system evolves as $\overline{3}_C$ of color if a single quark is removed in the DIS process. One then can examine the composition and fragmentation of this system. Some of the main issues in the nuclear case are nuclear modifications of leading particle effects due to increased density of comovers [8], nuclear modifications of intrinsic sea distributions in the target fragmentation region, particularly intrinsic charm, production of heavy quarkonia at large x_F, etc.

The forward proton fragmentation regime is a challenge to instrument at HERA, but it may be feasible to tag special channels involving neutral hadrons or muons. In the case of the gas jet fixed target ep collisions at HERMES, the target fragments emerge at low velocity and large backward angles, and thus may more be accessible to precise measurement.

I thank J. D. Bjorken, P . Hoyer, A. Hebecker, A. Mueller, E. Quack, and R. Vogt for helpful discussions. Work supported by the Department of Energy, contract DE–AC03–76SF00515.

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