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**“RAPIDITY GAP” EVENTS AND SHADOWING
IN DEEP INELASTIC SCATTERING**

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ABSTRACT

We suggest that the “rapidity gap” events reported from HERA are essentially the diffraction dissociation channels corresponding to the scaling shadowing seen on nuclei. We stress the interest of checking for virtual photons the old “inelastic optical theorem” relation connecting diffraction dissociation of the photon and the total cross section . We explain how it is possible at high q^2 to have shadowing, if this relation holds, even though diffractive processes– narrowly defined– become negligible in the total rate.

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The “shadowing effect”, where a non-strongly interacting particle –the photon– nevertheless shows absorption effects on nuclei, was proposed¹ as the reflection of certain quasi- elastic, “diffraction dissociation” processes. For real, $q^2 = 0$ photons these processes are the two-body production of the lightest vector mesons (rho, omega, phi). However, since the importance of these simple vector meson channels apparently declines with increasing q^2 , it might be supposed that shadowing will disappear in deep inelastic scattering .

Alternatively, it can be argued that in the scaling limit, where an increasing energy ν is available with increasing q^2 , that the diffraction production of new states will arise to take the place of these simple ones, giving a persistence of shadowing². This second point of view is reinforced by the observation that the “coherence length” or “fluctuation length”, whose large value at high energy underlies these phenomena, can remain large despite an increasing q^2 . For virtual photons³ this length involves $x = q^2/2m_p\nu$ (see below).

Experiments of the last several years appear to have decided definitely in favor of shadowing, with scaling, in deep inelastic scattering . The EMC⁴ found evidence of shadowing at high q^2 and with the NMC⁵ and E665 at Fermilab⁶ clear evidence, extending down to very small x on a series of nuclei has been seen. The effect apparently scales, approaches the real photon value as Bjorken x goes to zero, and goes away with increasing x .

If then, shadowing is there, where are the diffraction dissociation processes that go with it?

One of the interesting observations from early running at HERA⁷ is the existence of a class of “rapidity gap” events where an isolated group of particles is seen in the direction of the virtual photon. Such events would fit the description of the diffractive events to be associated with shadowing, if the target proton stays intact and has a small enough recoil, corresponding to a long enough coherence length.

If this association is correct, there must be a substantial production of these quasielastic states. The condition for a long enough coherence or fluctuation length l is

$$l \geq R \tag{1}$$

where³

$$l = \frac{2\nu}{q^2 + m_d^2} = \frac{1}{m_p x + m_d^2/2\nu} \quad (2)$$

with m_d the mass of the diffracted system, m_p the mass of the proton and R the radius of the nucleus in question. In terms of the uncertainty principle, this length may be viewed as the distance in the rest frame of the target the virtual system of mass m_d can travel. Equivalently, its inverse is the minimum recoil that must be taken up by the target to materialize the system m_d ; $1/l$ is the minimum (i.e longitudinal) momentum transfer. Thus for l to remain large in the deep inelastic scattering limit the relevant m_d must grow slower than, or at most equally fast as, ν . If we assume this, then with $R \approx A^{1/3}1.2f = A^{1/3}/160MeV$, the x term in eq.(2) must satisfy $x \leq (few) \cdot 10^{-2}$ or so. This certainly includes the x region where shadowing has been seen and fits with its disappearance around $x = 2 \cdot 10^{-2}$ nicely.

Quantitatively, the m_d constraint implies that to contribute to shadowing on nuclei a diffractive state must have sufficiently low mass, on the order $m_d^2/2\nu \leq 100MeV$. Conversely, the persistence of shadowing implies that such low mass states must be produced on protons by virtual photons, even at high q^2 . We note that the disappearance of shadowing as x increases might, but does not necessarily, imply a parallel disappearance of diffraction dissociation on protons; the decrease of l with x in eq.(2) is simply a kinematic effect, and can by itself cause shadowing to go away.

Concerning the rate of production of such states, various models, often in the language of the parton model and QCD⁸ or in a Pomeron formalism⁹ have been presented on this subject. Here we would simply like to recall that for real photons^{1,3} a certain relation held among the forward amplitude $f_{\gamma v}$ for photoproduction of a vector meson v , the forward elastic amplitude for v on nucleons f_{vv} , and the forward amplitude for the photon $f_{\gamma\gamma}$, viz. $f_{\gamma v}^2/f_{vv} = f_{\gamma\gamma}$ (by “forward” we mean at zero degrees in the photon direction). These amplitudes all refer to the reaction on nucleons and are presumed to be essentially imaginary, thus via the optical theorem $f_{\gamma\gamma}$ is essentially the total cross section for the photon and f_{vv} that for the hadron v . This relation is based on the idea that the hadronic component of the photon is dominant and “diffracts” off the nucleons. Although f_{vv} is not directly known, vector or hadron dominance suggests further $gf_{vv} = f_{\gamma v}$ where g is a photon-hadron coupling constant. Since for real photons g can be found from the leptonic decay widths of the vector mesons, this gave a relation among experimentally available quantities, which seems

to work well^{10,11}.

The persistence of shadowing for virtual photons strongly suggests that a similar “inelastic optical theorem” should hold at small x in deep inelastic scattering. The simplest assumption, and one that can be experimentally tested, would be that the same relation holds, where we identify the entire forward jet “d” with v :

$$g^2 \frac{d\sigma_d}{dt} \Big|_0 = \frac{1}{16\pi} \sigma_{total}^2, \quad (3)$$

The cross sections in eq.(3) for virtual photons may be found through the relation between the structure functions and σ_t in deep inelastic scattering¹² ($\sigma_t = (4\pi^2\alpha/q^2)F_2$). The forward production cross section $\frac{d\sigma_d}{dt}$ is a sum over cross sections (found analogously to σ_t) to all quasi-elastic states, and with no proton fragmentation. Since we must satisfy the coherence length criterion, we can define “quasi-elastic” as say $m_d^2/2\nu \leq 100\text{MeV}$. We anticipate, as is necessary for the consistency of the whole approach, that the value of $\frac{d\sigma_d}{dt}$ is not very sensitive to the precise value of the cutoff in m_d . The resulting cross section is then to be taken to the forward direction ($t \approx 0$). Since m_d , for a given x , determines the longitudinal momentum transfer, the sum over m_d may also be viewed as an integral over the longitudinal momentum transfer up to about 100MeV, t referring then to the transverse momentum transfer squared. In writing eq (3) we assume the amplitudes to be purely imaginary and the forward jet “d” to be dominated by states with “photon like” quantum numbers.

Since for virtual photons we now have no independent way of finding g^2 , we regard it as a parameter to be determined, having the interpretation of the probability of the hadronic component in the photon. We may claim the relation works if g^2 comes out roughly on the order of α ; for comparison, with real photons we had¹¹ $g^2 \approx 0.5 \alpha$. The relation is intended to hold for every q^2 and ν with x sufficiently small, say $x \leq (few) \cdot 10^{-2}$.

Eq.(3) is nontrivial in view of its nonlinearity. This is interesting when combined with scaling behavior. From scaling (we neglect scaling violation for the present purposes) $\sigma_{total} \sim 1/q^2$, thus for the left-hand -side of eq.(3) we expect $\sim 1/q^4$. Since we wish g to remain on the order of α , we cannot allow it vary strongly with q^2 . Thus

$$\frac{d\sigma_d}{dt} \sim 1/q^4. \quad (4)$$

That is, we have naive dimensional scaling, with g simply a function of x , corresponding to the fact that it is dimensionless.

However, it should be stressed that the dimensional scaling of a quantity like $\frac{d\sigma_d}{dt}$ is by no means self-evident. A mass or a scale would seem to be implicit in its definition through the requirement that the target proton remain intact or that the momentum transfer be less than a certain value. In fact we seem to run into trouble immediately when we consider the integral of $\frac{d\sigma_d}{dt}$ over t . If we wish the resulting total cross section for diffraction dissociation (with intact target protons) to scale, it would seem that we must require that the slope in t also scales, which in turn implies that the recoil spectrum for the proton become flat in t in the deep inelastic limit. This seems entirely implausible, however; we are asking that the proton take up an indefinitely large recoil without breakup¹³.

Another solution, however, suggests itself: the integrated (single) diffraction dissociation cross section could be allowed to go to zero relative to the total cross section. That is, we can have $\frac{d\sigma_d}{dt}$ scaling as in eq.(4), and the slope in t more or less conventionally constant. Then the result of the integral over t contains a scale, but the integral falls faster than $1/q^2$ and so goes to zero, relative to the total cross section; therefore there is no violation of scaling for the total cross section. Since eq.(3) is maintained we nevertheless get shadowing. Thus the conclusion at the end of the first paragraph may have been too hasty and in a certain sense we can have vanishing diffraction dissociation and shadowing at the same time— if by diffraction dissociation we mean events with an isolated proton undergoing a small momentum transfer.

In this picture there is also an attractive symmetry between the forward and backward directions: just as the purely “elastic” production in the virtual photon direction, namely rho- photoproduction, disappears in the scaling limit, so does the purely elastic “intact proton” process disappear in the proton direction. Scaling can be expected to occur when we allow both the forward and backward systems to fragment. In view of the freedom of the proton to fragment unseen in the present detectors — ref[7] cites a hole of three units in rapidity around the proton direction — this could be compatible with the rough q^2 independence claimed⁷ for the “rapidity gap” events as a fraction of the total. Although for shadowing on nuclei our primary interest is the final state where the proton is intact, processes with soft proton fragmentation, presumably the bulk of the events, should be quite similar in their characteristics.

If all this is true, an interesting picture emerges in the diffractive regime for real particles on the one hand and highly virtual ones on the other. In both cases a relation like eq.(3) is true (for hadrons with $g^2 \sim 1$). But while for real particles the total cross section for purely elastic or single diffraction dissociation scattering is approximately a constant part of the total, in the highly virtual situation scaling forces us to the conclusion that such processes disappear in the total rate. This might be understood by saying that all even partially exclusive processes must vanish in the deep inelastic limit in the sense of the total rate, but nevertheless diffraction and shadowing are still present in the sense of eq.(3). This picture makes it easier to understand how the apparently “soft”, long ranged, shadowing and diffraction effects can coexist with the “hard”, short ranged, parton model. The parton processes on proton targets may be calculated in the usual way. Their second order iteration is elastic scattering of the photon, which also has a hadronic partner, diffraction dissociation of the photon. These are not ordinary partonic processes and do not populate the whole rapidity interval. Like the photon elastic scattering, diffraction dissociation falls with a higher power of q^2 than the total cross section, but it can influence the scaling level through interference, as in shadowing on complex targets.

It will be interesting to see if experiment bears this picture out.

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10. A thorough review of the subject is given by T.H. Bauer, R.D. Spital, D.R. Yennie and F.M. Pipkin, Rev. Mod. Phys. **50** 261 (1978).
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12. R. P. Feynman, *Photon-Hadron Interactions* pg.127; Benjamin, 1972. The "t" here refers to "transverse", and we use $F_2 \approx 2xF_1$. Although the analog of the total cross section for virtual photons is not entirely unambiguous, (see for example the remarks in footnote 23 of Bauer et al.) the difference between different plausible definitions is small at small x -and probably not so significant as the error we make in neglecting σ_s .
13. I am grateful to N. N. Nikolaev for emphasizing this point. In the approach of ref. 8 for example, things work differently: $\frac{d\sigma_d}{dt} \sim c/q^2$, (c a constant with dimensions) while the slope in t remains constant. This leads to an integrated cross section for diffraction dissociation with intact target protons $\sim 1/q^2$, i.e. a constant fraction of the total cross section . Similiarly in ref. 9, single diffraction dissociation is a scaling process with a constant fraction of the total cross section unlike our conclusions.