WHAT ONE CAN LEARN ABOUT QCD FROM NUCLEAR BEAMS AT HERA * **

M. Strikman

Pennsylvania State University
University Park
PA 16802

(Received October 15, 1996)

Overview is given of the theoretical issues of the physics which can be addressed with nuclear beams circulating in HERA. It is shown that such experiments widen considerably the horizon for probing QCD compared to that from free nucleon targets. They would allow to study nonlinear QCD phenomena at small x, understand dynamics of nuclear shadowing, as well as the the origin of diffraction in deep inelastic scattering. Interplay between the physics to be studied at HERA and in AA collisions at RHIC and LHC is also discussed.

PACS numbers: 12.38. Bx, 13.60. -r, 13.60. Hb

1. Introduction

The successes of QCD in describing *inclusive* perturbative phenomena have moved the focus of investigations to new frontiers. Three fundamental questions to be resolved are the space-time structure of high-energy strong interactions, the QCD dynamics in the nonlinear, small coupling domain and the QCD dynamics of interactions of fast, compact colour singlet systems.

The study of electron-nucleus scattering at HERA allows a new regime to be probed experimentally for the first time. This is the regime in which the virtual photon interacts coherently with all the nucleons at a given impact parameter. In the rest frame of the nucleus this can be visualized in terms of the propagation of a small $q\bar{q}$ pair in high density gluon fields over much larger distances than is possible with free nucleons. In the Breit frame it corresponds to the fact that small x partons cannot be localized longitudinally to better than the size of the nucleus. Thus low x partons

* Presented at the XXXVI Cracow School of Theoretical Physics, Zakopane, Poland, June 1–11, 1996.

** Based on the theory contribution to the report of the conveners of the working group "Light and Heavy Nuclei", in the framework of the study "Future of HERA"[1] from different nucleons overlap spatially creating much larger parton densities than in the free nucleon case. This leads to **a large amplification of the nonlinear effects expected in QCD at small x.** The HERA *ep* data have confirmed the rapid increase of the parton densities in the small x limit predicted by perturbative QCD. However the limited x range available at HERA makes it difficult to distinguish between the predictions of the DGLAP evolution equations and the BFKL-type dynamics. Moreover, the nonlinear effects expected at small x are relatively small in *ep* scattering in the HERA kinematic domain and it may be necessary to reduce x by at least one order of magnitude to observe unambiguously such effects. However, the amplification obtained with heavy nuclear targets **allows an effective reduction of about two orders of magnitude in x** making it feasible to explore such nonlinear effects at the energies available at HERA. The question of nonlinear effects is one of the most fundamental in QCD. It is crucial for understanding the kind of dynamics which would slow down and eventually stop the rapid growth of the cross section (or the structure function, F_2) at small x. It is also essential in order to understand down to what values of x the decomposition of the cross section into terms with different powers of $\frac{1}{Q^2}$ remains effective. It is important for the understanding of the relationship between hard and soft physics. One can also study the dynamics of QCD at high densities and at zero temperatures raising questions complementary to those addressed in the search for a quark–gluon plasma in high-energy heavy ion collisions.

Deep inelastic scattering from nuclei provides also a number of ways to probe **the dynamics of high-energy interactions of small colour singlet systems.** This issue started from the work of Gribov [2] who demonstrated the following paradox. If one makes the natural (in soft physics) assumption that at high energies any hadron interacts with a heavy nucleus with cross section $2\pi R_A^2$ (corresponding to interaction with a black body), Bjorken scaling at small x is grossly violated — $\sigma_{\gamma^* A} \propto \ln Q^2$ instead of $\frac{1}{Q^2}$. To preserve scaling, Bjorken suggested, using parton model arguments, that only configurations with small $p_t \leq p_{t0}$ are involved in the interaction (the Aligned Jet Model) [3]. However, in perturbative QCD Bjorken's assumption does not hold — large p_t configurations interact with finite though small cross sections (colour screening), which however increase rapidly with incident energy due to the increase of the gluon density with decreasing x. Hence again one is faced with a fundamental question which can only be answered experimentally: *Can* **small** *colour singlets interact with hadrons with cross sections comparable to that of normal hadrons?* At HERA one can both establish the x, Q^2 range where the cross section of small colour singlets is small — *colour transparency*, and look for the onset of the new regime of large cross sections, *perturbative colour opacity.*

Another fundamental question to be addressed is **the propagation of quarks through nuclear matter.** At large energies perturbative QCD leads to the analogue of the Landau–Migdal–Pomeranchuk effect in quantum electrodynamics. In particular Baier *et al.* [4] find a highly nontrivial dependence of the energy loss on the distance, L, traveled by a parton in a nuclear medium: the loss instead of being $\propto L$ is $\propto L^2$. Several manifestations of this phenomenon can be studied at HERA. This important question will not be discussed in this lecture.

There is also an *important connection to heavy ion physics.* Study of eA scattering at HERA would be important for the analysis of heavy ion collisions at the LHC and RHIC. Measurements of gluon shadowing at small x are necessary for a reliable interpretation of the high p_t jet rates at the LHC. In addition, the study of parton propagation in nuclear media is important for the analysis of jet quenching phenomena, which may be one of the most direct global signals of the formation of a quark–gluon plasma.

Current fixed target data on lepton–nucleus scattering only touch the surface of all these effects due to the limited Q^2 range of the data at small x. Indeed the Q^2 range of these data is too small to distinguish the contribution of the vector meson dominance behaviour of the photon from its hard QCD behaviour at small x. The range of x and Q^2 in experiments with nuclei at HERA compared to the fixed target experiments extends a factor of 100 down in x.

In this lecture I will focus on several phenomena where *HERA has a great potential for discovery of new phenomena* already with rather modest luminosities between 1-10 pb^{-1} per nucleon with the existing detectors. With the forthcoming upgrades this would require between 1 and 6 months of HERA running with nuclear beams. These new phenomena include:

• **Observation and detailed study of the x and Q^2 dependence of nuclear shadowing over a wide Q^2 deep inelastic range.** This will allow the processes limiting the growth of F_2 as x tends to zero to be studied in detail.

• **Observation of the difference between the gluon distributions in nuclei and free nucleons.** This will allow to study directly the most nonlinear interactions in QCD which occur in the gluon sector the shadowing process to be studied directly.

• **Discovery of differences between the structure of Pomeron generated diffraction of nucleons and nuclei.** Use of nuclei would allow to vary relative contribution of the Pomeron coupling to weakly and strongly interacting configurations in the photon and hence shed a new light on the interplay of soft and hard physics in diffraction in deep inelastic scattering.

• **Discovery of colour transparency at ultra-high energies and study of onset of colour opacity.** Study of coherent diffractive production vector mesons, dijets, etc would allow to search for colour transparency which may at the top of HERA energies gradually disappear signaling onset of a new phenomenon — perturbative colour opacity — strong interaction of fast small objects.

2. Space-time picture of DIS off nuclei at small x

2.1. The rest frame

In the rest frame of the target nucleus the life-time of a fluctuation is given by the formula

$$\tau = \frac{\beta}{m_N x_{Bj}}, \qquad x = x_{Bj}, \tag{1}$$

where $\beta = Q^2/(Q^2+M^2) < 1$. M is the mass of the $q\bar{q}$ system, $M^2 = \frac{k_t^2+m_q^2}{z(1-z)}$, and z is the light-cone momentum fraction, k_t the transverse momentum and m_q the mass of the quark. Perturbative QCD studies show that the most probable configurations are those for which $M^2 \approx Q^2$. In the case of transversely polarized photons both configurations with small k_t and highly asymmetric fractions z, and configurations with comparable z and $1-z$ contribute to the cross section. For the case of the longitudinal photons the soft (small k_t) asymmetric contribution is strongly suppressed.

In the language of noncovariant diagrams this corresponds to the virtual photon fluctuating into a quark–antiquark pair at a longitudinal distance:

$$l_c = \frac{\beta}{m_N x}, \tag{2}$$

from the nucleus which far exceeds the nuclear radius. The distance l_c is referred to as the "coherence length". The pair propagates essentially without transverse expansion until it reaches the target. QCD evolution leads to a logarithmic decrease of β with increasing Q^2. At HERA coherence lengths of up to 1000 fm are possible, so that the interaction of the $q\bar{q}$ pair with nuclear matter can be studied in detail — notably its transparency to small size pairs — *colour transparency.*

At energies available at HERA new features of colour transparency should emerge: the incident small size $q\bar{q}$ pair resolves small x gluon fields with virtualities $\sim Q^2$. If the transverse size of the $q\bar{q}$ pair is $r_t = b_q - b_{\bar{q}}$, the cross section for interaction with a nucleon is [5]

$$\sigma_{q\bar{q},N}(E_{\rm inc}) = \frac{\pi^2}{3} r_t^2 \alpha_s(Q^2) x g_N(x,Q^2), \tag{3}$$

where $Q^2 \approx \frac{\lambda(x)}{r_t^2}, \lambda(x \approx 10^{-3}) \approx 9, x = \frac{Q^2}{2m_N E_{\rm inc}}$. Since the gluon density increases rapidly with decreasing x, even small size pairs may interact strongly, leading to some sort of *perturbative colour opacity* — the interaction of a small object with a large object with a cross section comparable to the geometric size of the larger object (Fig. 1).

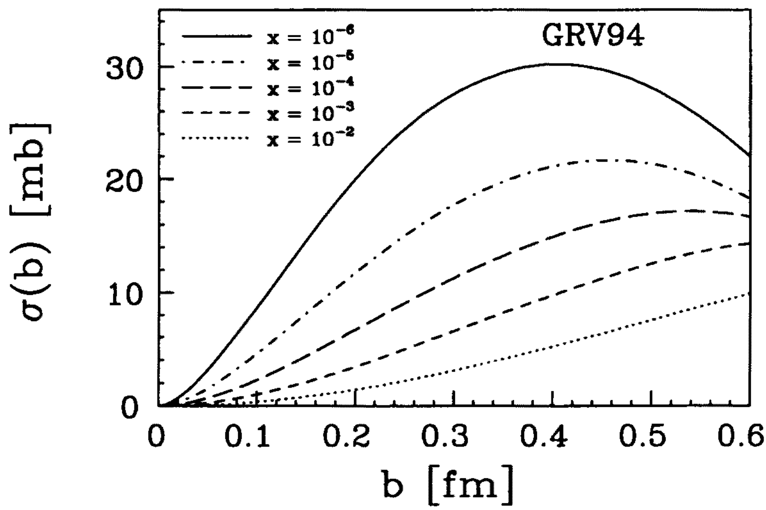

Fig. 1. Colour-dipole cross section, $\sigma_{q\bar{q}N}(x,b)$ of Eq. (3), as a function of the transverse size of the $q\bar{q}$ pair for various values of x and for the GRV94 parameterization of the nucleon's gluon density.

Unitarity considerations for the scattering of a small size system — *i.e.* the requirement that $\sigma_{\rm inel}(q\bar{q}, {\rm target}) \leq \pi R^2_{\rm target}$ — as well as requirement of positivity of the partial cross sections [6] indicate that nonlinear effects (*i.e.* effects not accounted for by the standard evolution equations) should become significant at much larger values of x in eA scattering than in ep scattering.

2.2. The Breit frame

In the Breit frame, small x partons in a nucleon are localized within a longitudinal distance $\sim 1/xp_N$, while the distance between two nucleons is $\sim r_{NN}m_N/p_N$ (r_{NN} is the distance between nucleons in the rest frame and p_N is the nucleon momentum). Therefore partons with $x < 1/(2m_N r_A)$, where $r_A \approx r_0 A^{1/3}$ fm is the nuclear radius and $r_0 = 1.1$ fm, cannot be localized to better than the whole nuclear longitudinal size. Hence low x partons emitted by different nucleons in a nucleus can overlap spatially and fuse, provided the density is high enough, leading to shadowing of the

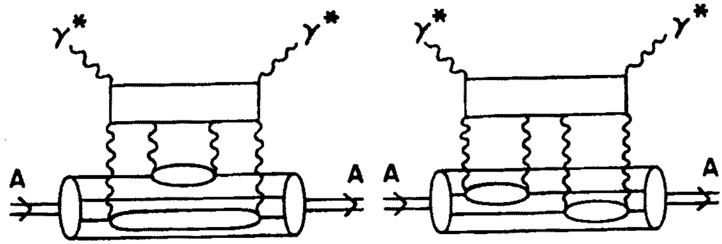

Fig. 2. Typical fan diagrams leading to nonlinear evolution of $g_A(x,Q^2)$.

nuclear partonic distributions with respect to the free nucleon ones and to nonlinear effects already at values of $x \sim 10^{-4} \div 10^{-3}$. For example, in the simplest model of nonlinear effects corresponding to the fan diagrams of Fig. 2, the additional contribution $\delta g_A(x,Q^2)$ to $g_A(x,Q^2)$ due to the nonlinear term in the equation for the Q^2, x evolution of the gluon density is [7]:

$$Q^2 \frac{\partial}{\partial Q^2} \frac{\delta x g_A(x,Q^2)}{A} = -\frac{81}{16} \frac{A^{1/3}}{Q^2 r_0^2} \alpha_s^2(Q^2) \int_x^1 \frac{du}{u} \left[u g_N(u,Q^2)\right]^2 . \qquad (4)$$

The analogous equation for the gluon density in the nucleon has a much smaller coefficient — approximately by a factor $r_0^2/r_N^2 A^{1/3}$, where $r_N \sim 0.8$ fm is the nucleon radius. Once again one can see then that the x-range where nonlinear effects become significant differs for a heavy nucleus and for a nucleon by more than two orders of magnitude, assuming $x g_N(x,Q^2) \propto x^n$ with $n \sim -0.2$.

Thus electron–nucleus collisions at HERA can be seen as efficient amplifiers of nonlinear QCD effects.

2.3. Theoretical framework for small x phenomena in eA collisions

2.3.1. Perturbative and nonperturbative shadowing

At small x the DIS cross section per nucleon in a nucleus is smaller than for a free one, the so called shadowing phenomenon. Shadowing is determined by a combination of non-perturbative and perturbative effects. In the DGLAP evolution equations one can express shadowing at large Q^2 through the shadowing at the normalization point Q_0^2. This type of shadowing is connected to the soft physics. It can be visualized *e.g.* in the aligned jet model of Bjorken [3], extended to account for QCD evolution effects [8]. A virtual photon converts to a $q\bar{q}$ pair with small transverse

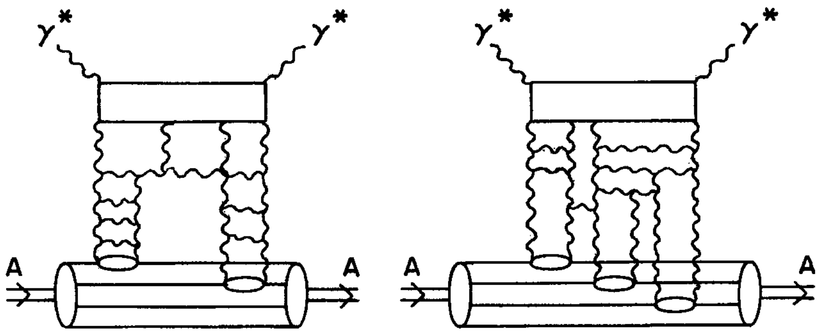

Fig. 3. Examples of typical perturbative QCD diagrams contributing to nuclear shadowing.

momenta (large transverse size) which interacts with the nucleus with a hadronic cross section, leading to shadowing. The effective small phase volume of these configurations ($\propto \frac{\lambda}{Q^2}$) leads to Bjorken scaling and it is due to colour transparency [8].

At large Q^2, these $q\bar{q}$ pairs evolve into systems with gluons, leading to a shift of shadowing to smaller x, which is equivalent to the standard Q^2 evolution of parton distributions. These $q\bar{q}$ pairs, which interact with the target nonperturbatively, seem to be responsible for most of the shadowing at intermediate Q^2 and $x \sim 10^{-2}$ which has been studied at fixed target energies. This mechanism of shadowing is effective for σ_T only since for σ_L the aligned jet contribution is strongly suppressed. For σ_L (as well as for the production of heavy quarks) one is more sensitive to the shadowing due to the interaction of small size $q\bar{q}$ pairs with the nuclear gluon field which can be shadowed.

At smaller x the situation may change rather dramatically because, as the recent HERA data indicate, already for $Q^2 \sim 1.5$ GeV^2 at $x \sim 10^{-4}$ perturbative contributions to $F_{2p}(x, Q^2)$ appear to become important, leading to a rapid increase of the structure functions with decreasing x. Hence contributions of various perturbative mechanisms which may generate shadowing for configurations of a size smaller than the hadronic size may become important. Perturbative QCD may be applicable to those small size pairs. Typical contributions involve diagrams of the eikonal type, various enhanced diagrams, *etc.* (Fig. 2, 3).

3. Shadowing and diffraction

In practically all models it is assumed that nuclei are built of nucleons. So the condition that the matrix element $< A|T[J_\mu(y), J_\nu(0)]|A >$ involves only nucleonic initial and final states is implemented[1]. Under these natural assumptions one is essentially not sensitive to any details of the nuclear structure, such as short-range correlations *etc.*

In the case of scattering off the deuteron and light nuclei the same diagrams contribute to the cross section for diffraction in *ep* scattering and the cross section for shadowing — hence similar nonlinear phenomena like those described by Eq. (4) are involved in each case. For example for the deuteron [10]:

$$\sigma_{\rm shad} = \frac{\sigma_{\rm tot}(eD) - 2\sigma_{\rm tot}(eN)}{\sigma(eN)} = \frac{\left.\frac{d\sigma_{\rm diff}(ep)}{dt}\right|_{t=0}}{\sigma_{\rm tot}(ep)} \frac{1}{8\pi R_D^2} R, \tag{5}$$

where $R = \frac{(1-\lambda^2)}{(1+\lambda^2)}$, $\lambda = ReA/ImA \approx \frac{\pi}{2}\frac{\partial \ln A}{\partial \ln s}$ for the amplitude A of $\gamma^* p$ scattering and R_D is the deuteron radius. For small x, λ may be as large as 0.5, leading to $R \sim 0.5$ especially for the case of the longitudinal cross section. So already for light nuclei the study of the total cross sections of scattering from nuclei would allow *to establish a fundamental connection between the two seemingly unrelated phenomena of diffraction at small t in ep scattering and nuclear shadowing.* With the increase of A more complicated nonlinear interactions with several nucleons become important, see *e.g.* Fig. 3b.

Nuclear shadowing for the total cross sections has a simple physical meaning - it corresponds to a reduction of cross section due to screening of one nucleon by another (as well as by several nucleons for $A > 2$). If one treats the deuteron as a two nucleon system it is possible to apply the Abramovskii, Gribov, Kancheli (AGK) cutting rules [11] to elucidate **the connection between nuclear shadowing, diffraction and fluctuations of multiplicity.** One observes that the simultaneous interaction of the γ^* with the two nucleons of the deuteron modifies not only the total cross section (Fig. 4a) but also the composition of the produced final states. It increases the cross section for diffractive scattering off the deuteron due to diffractive scattering off both nucleons by $\delta\sigma_{\rm diff} = \sigma_{\rm shad}$ — this is described by the imaginary part of the shadowing diagram of Fig. 4b. At the same time the probability to interact inelastically with one nucleon only is reduced since the second nucleon screens the first one: $\delta\sigma_{\rm single} = -4\sigma_{\rm shad}$ (the processes of Fig. 4c, d). In addition, a new process emerges in the case of the deuteron which was absent in the case of the free nucleon — *simultaneous*

[1] The condition that nuclei are built of nucleons is not so obvious in the fast frame picture. However it is implemented in most of the models [7, 9].

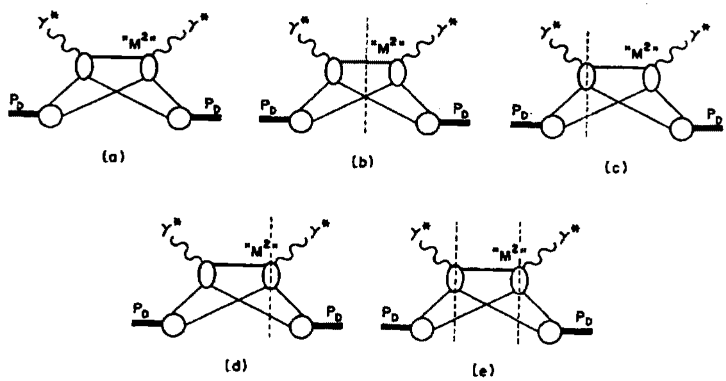

Fig. 4. Double rescattering diagram for the total cross section of scattering off the deuteron(a); Cuts of the double rescattering diagram corresponding to diffraction (b); screening of single scattering (c, d), double multiplicity (e).

inelastic interaction with both nucleons (the cut of two Pomeron exchanges — Fig. 4e) which leads to a factor of two larger multiplicity densities for rapidities away from the current fragmentation region: $\sigma_{\text{double}} = 2\sigma_{\text{shad}}$. Altogether these contributions constitute $-\sigma_{\text{shad}}$, the amount by which the total cross section is reduced [2]. To summarize, *there is a deep connection between the phenomena of diffraction observed at HERA in ep scattering and nuclear shadowing as well as the A-dependence of diffraction and the distribution of the multiplicities in DIS.*

It follows from the above discussion that it is possible to get information about the dynamics of nuclear shadowing and hence about nonlinear effects by studying several **key DIS phenomena** such as: nuclear shadowing for inclusive cross sections F_2^A, $\frac{\sigma_L}{\sigma_T}$, $F_2^{A\ \text{charm}}$; the cross section for nuclear diffraction; the multiplicity distribution for particle production in the central rapidity range; diffractive production of vector mesons. The advantage of the latter process is that one gets a rather direct access to the interaction of a small colour dipole with matter. It is in a sense an exclusive analogue of σ_L which is easier to measure.

3.1. The A-dependence of parton distributions at small x

As discussed above, the nucleus serves as an amplifier for nonlinear phenomena expected in QCD at small x. The simplest example of such effects is given by equation (4) where the nonlinear term is proportional to the

[2] For simplicity we give here relations for the case of purely imaginary $\gamma^* N$ amplitude $\frac{ReA}{ImA} = 0$.

square of the nucleon gluon density. If shadowing were absent the parton densities per unit transverse area would be enhanced by a factor $A^{1/3}$ as compared to the free nucleon case. Hence even just an upper limit on the parton densities based on unitarity — that the cross section for the inelastic interaction of a small dipole with a nucleus may not exceed $\sigma_{\rm inel} = \pi R_A^2$ — leads to the expectation of nonlinear phenomena — shadowing of an observable magnitude — already at $x \sim 10^{-3} \div 10^{-4}$ [6].

Hence, from detailed studies of the A-dependence of the parton densities it would be possible both to check the dominance of the two-nucleon screening mechanism for $x \gtrsim 10^{-2}$ where coherence length, l_c (Eq. 2) is comparable to the average internucleon distance, [12, 13] and to extract information about the coherent interaction of the virtual photon with three (four) nucleons at $x \leq 10^{-3}$.

For $x \geq 10^{-2}$ for any nucleus and for all x for light nuclei, the main contribution to shadowing is given by the interaction with two nucleons of the target. Hence in this regime there is a relatively simple connection with the diffraction of a virtual photon off a proton — which is the simplest nonlinear effect in the perturbative domain in QCD. For smaller x and heavy nuclei, when essential longitudinal distances become comparable and ultimately exceed the diameter of the nucleus, several nucleons at the same impact parameter contribute to the screening. It is worth emphasizing that these multi-vacuum exchange processes cannot be singled out unambiguously using a nucleon target. The relevant QCD diagrams for the total cross section of $\gamma^* A$ interaction are rather similar to higher-order nonlinear diagrams for the proton target — except that in the nuclear case one has to impose the condition that couplings to the individual nucleons are colour singlets, see *e.g.* Fig. 2, 3.

In a sense, the studies of nuclear shadowing at small x and large Q^2 can be considered as a simpler model of nonlinear effects which occur in the case of a nucleon target. In the latter case it is not easy to relate the coupling of say two vacuum exchanges (or a ladder with 4 gluons in the t-channel) with a nucleon to the coupling of one vacuum exchange with a nucleon. In fact the region of $10^{-3} \geq x \geq 10^{-4}$ may be optimal in this respect since nonlinearities for the nucleon case are still small though nonlinearities for the nuclear case are already quite substantial. It is worth emphasizing that experience of the studies of the total hadron–nucleus scattering indicates that interaction with bound nucleons for the total cross sections can well be approximated by the interactions with free nucleons (for a recent analysis see [14]). Therefore *nuclear structure effects do not obscure the interpretation of nuclear shadowing effects.* Using current information from HERA on diffractive production in *ep* scatter it is straightforward to estimate the amount of nuclear shadowing at small x taking into account interactions

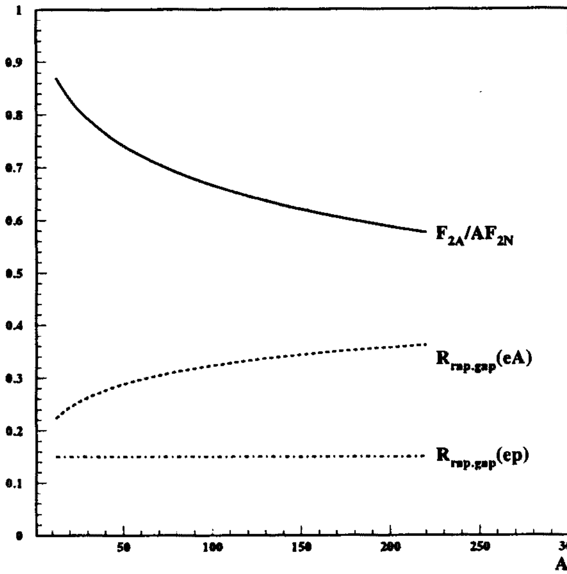

Fig. 5. A-dependence of nuclear shadowing and probability of rapidity gap events in the colour screening model of shadowing; dot-dashed curve assumes A-independent probability of rapidity gap events.

with 3 or more nucleons using the eikonal approximation with an effective cross section determined from diffractive data, see Eq. (6) below. The result of the calculation [17] is shown in Fig. 5 for $Re/Im = 0$; for $A \geq 12$ it weakly depends on the value of Re/Im. Since the data on diffraction indicate that the fraction of diffractive events in DIS weakly depends on x, Q^2 these considerations show that significant shadowing effects should be present for $F_2^A(x, Q^2)$ in the wide small x range of HERA. Note that the shadowing effect in DIS is expected to be much smaller than for the case of real photon scattering since the effective cross section for interaction of the hadron component of quasi-real photon at HERA is a factor of ~ 3 larger than for a highly virtual photon (we use here the HERA data on diffraction for real photons [15]).

Since the interaction of the octet colour dipole gg is a factor of $9/4$ stronger than for the $q\bar{q}$ dipole, nonlinear effects are expected to be more important for gluons. So gluon shadowing would provide even more direct access to nonlinear phenomena. Note that in this case there is no simple relation of shadowing with diffraction in $\gamma^* + p$ DIS, so any information about gluon shadowing would be complementary to the information from ep DIS. There are very few data on the gluon distribution in nuclei. Among them, the enhancement of the gluon distribution at $x \sim 0.1$ indicated by the inelastic J/ψ production data [16]. Also the analysis [18] of the scaling violation for the ratio F_2^{Sn}/F_2^C measured recently by NMC under the assumption that higher twist effects are not important in the Q^2, x range of the data allows to extract information about the A-dependence of gluon distributions, indicating some nuclear shadowing for G_A for $x \leq 0.01$ and an enhancement at $x \sim 0.1$, see Figure in [18][3]. Theoretical expectations for gluon shadowing discussed in the literature are quite different — from a larger effect than for F_2^A [21], to an effect comparable to that of quarks [20, 19, 22, 23] to substantially smaller shadowing [24]; see also contributed papers to proceedings of the HERA workshop.

Comparison of different determinations of shadowing of gluons: high p_t jet production, incoherent J/Ψ-meson production, and measurements of the scaling violation for the F_2^A/F_2^D ratios will allow to determine the range of applicability of the DGLAP evolution equations and hence provide unique clues to the role of nonlinear effects.

It is worth emphasizing also that knowledge of parton distributions in nuclei at these values of x will be crucial also for studies in heavy-ion physics at the LHC and RHIC.

4. Diffraction off nuclei

4.1. Introduction

The measurements of the ZEUS and H1 collaborations of deep-inelastic electron-proton scattering have revealed the existence of a distinct class of events in which there is no hadronic energy flow in an interval of pseudorapidity, η, adjacent to the proton beam direction *i.e.* events with a large rapidity gap. Such events are interpreted as deep inelastic scattering from the Pomeron, $I\!P$. Studies of events with a large rapidity gap from nuclear targets will allow the structure of the Pomeron from a different source than the free nucleon to be determined. It will be interesting to see if these structures differ. In addition, the study of diffractive vector meson production will be interesting to search for the phenomenon of colour transparency. Such a phenomenon has not yet been convincingly seen although it is predicted in QCD.

Diffraction studies have been defined as one of the primary goals of nuclear beams in HERA. Such processes can be interpreted using two complementary languages depending on whether the rest frame of the nucleon or the Breit frame are used:

[3] The shadowing for gluons should be accompanied by a significant enhancement at larger x since the total momentum fraction carried by gluons in nuclei is not suppressed and is probably slightly enhanced [19].

• Scattering of electrons on colourless components of the proton. Such scattering may be identified, for the very low x events dominated by diffraction, with the interaction with the vacuum t-channel exchange which is often referred to as the Pomeron, $I\!P$. This object is not necessarily the same as the Pomeron of the Gribov–Regge high-energy soft interactions (see report of the diffractive group of the HERA workshop [26]). Deep inelastic electron scattering leading to the presence of a rapidity gap can thus be considered as probing the internal parton structure of the $I\!P$ originating from the proton.

One of the questions of primordial importance which may be addressed within the future electron-nucleus scattering program at HERA is then "how universal is the internal structure of the Pomeron?" or, more precisely: "Is the internal structure of the Pomeron originating from various hadronic sources (protons, neutrons, nuclei) the same?". We shall show below how nuclei may help in answering these questions.

• The diffractive interaction of different hadronic components of the virtual photon with the target via vacuum exchange. Diffraction predominantly selects the γ^* components which interact with sufficiently large cross sections such as large transverse size $q\bar{q}$, $q\bar{q}g$ colour dipoles. Therefore the study of diffraction plays a very important role in determining the relative importance of small and large size configurations and addressing the question whether small white objects interact weakly or not. Indeed if the interaction with a target becomes sufficiently strong at small impact parameters the cross section for diffraction (which includes both elastic scattering and inelastic diffractive dissociation) would reach the black body limit of 50% of the total cross section.

4.2. Theoretical expectations

Diffraction off a nucleon (including dissociation of the nucleon) constitutes about 15-20% of the deep inelastic events. Therefore the interaction is definitely far from being close to the scattering off a black body. Even this number came a surprise in view of the large Q^2 value involved. Using the generalized optical theorem as formulated by Miettinen and Pumplin, one can estimate the effective total cross section for the interaction of the hadronic components of the γ^* as

$$\sigma_{\rm eff} = 16\pi \frac{\left.\frac{d\sigma_{\rm diff}^{\gamma^*+p\to X+p}}{dt}\right|_{t=0}}{\sigma_{\rm tot}(\gamma^* N)} \approx 12 \div 15 {\rm mb}. \qquad (6)$$

This cross section is significantly smaller than the ρN cross section which at the HERA energies can be estimated to be close to 40 mb using the vector dominance model and the Landshoff–Donnachie fit [25]:

$$\sigma_{\rm tot}^{\rho N}(s) = \sigma_{\rm tot}^{\rho N}(s_0)\left(\frac{s}{s_0}\right)^n, \tag{7}$$

where $n \approx 0.08, s_0 = 200\ \mathrm{GeV}^2, \sigma_{\rm tot}^{\rho N}(s_0) = 25$ mb. However it is sufficiently large to result in a substantial cross section of diffraction for small x — it can reach 30-40% for large A (Fig. 5)[17]. For large A the coherent diffraction dominates when the incoming wave is sufficiently absorbed at small impact parameters which, by virtue of Babinet's principle, corresponds to scattering beyond the nucleus. In such processes the nucleus remains intact and the average momentum transfer is very small ($\langle t\rangle \propto A^{-2/3}$).

One expects that hadronic configurations interacting with different strength contribute to diffraction (*c.f.* Fig. 1). The parameter $\sigma_{\rm eff}$ characterizes just the average strength of this interaction, while the distribution over the strengths is expected to be quite broad. The study of diffraction off nuclei allows us to separate contributions to diffraction of large and small size configurations due to **the filtering phenomenon**: with the increase of A the relative contribution of more weakly interacting (smaller size) configurations should increase since they are less shadowed, leading to a relative enhancement of the colour transparent subprocesses.

Examples of promising processes are:

- Diffractive production of charm. The A-dependence of this process would be interesting already at low Q^2 since the essential transverse distances are, naively, of the order of $1/m_c$, where m_c is the charm quark mass. Since the cross section for the interaction of a colour dipole of such size is small for $x \sim 10^{-2}$, the cross section for diffractive charm production at these values of x is small and practically not shadowed, leading to a cross section $\propto A^{4/3}$. At the same time the $c\bar{c} - N$ cross section increases rapidly with decreasing x (increase of energy) for fixed Q^2. Therefore at HERA energies diffractive charm production in ep collisions may become a substantial part of the total diffractive cross section. At this point one expects the emergence of shadowing in diffractive charm production in eA collisions, leading to slowing down of the A-dependence of diffractive charm production as compared with the A dependence at $x \sim 10^{-2}$. One can go one step further and study the A-dependence of p_t distributions for diffractive charm production. Smaller size components will be less absorbed and so their relative contribution may increase with A.
- Diffractive production of two high p_t jets.

  Selection of large p_t jets enhances the contribution of diffraction of small size configurations. Hence, one expects broader p_t distributions in the case of nuclear targets (smaller jet alignment) with nontrivial dependences on W and Q^2. For example, if we fix the p_t of the jets, the A-dependence of dijet production should become weaker with increasing energy reflecting the increase of the absorption (which can be studied this way). If on the other hand we fix W and consider the A-dependence as a function of p_t, a stronger A-dependence is expected at high p_t. Effectively, this would be another way to approach colour transparency via filtering out of the soft components.

To summarize, a study of inclusive diffraction will give better insights into the structure of the Pomeron. The interplay of soft and hard contributions will lead to a breakdown of factorization for the structure function of the Pomeron. Stated differently, the check of the degree of "universality" of the Pomeron — *i.e.* whether the "nuclear" Pomeron is different from the Pomeron observed in *ep* diffraction — will provide a very sensitive test of QCD dynamics.

An important aspect of the diffractive studies is the colour transparency phenomenon. In view of its special interest we will discuss this separately below.

4.2.1. Multiplicity fluctuations

As we explained in section 3 diffraction off nuclei and nuclear shadowing are closely related to the simultaneous inelastic interactions of the virtual photon with several nucleons. Such interactions produce events with large multiplicity densities in the central rapidity range, leading to a much broader distribution over multiplicities in *eA* collisions than in the *ep* case. Study of this effect will provide information complementary to that obtained from nuclear shadowing about the structure of the vacuum exchange at small x. Interesting phenomena to look for may be:

1. Local fluctuations of multiplicity in the central rapidity region, *e.g.* the observation of a broader distribution of the number of particles per unit rapidity, $n(\Delta\eta)$, than in *ep* scattering [17], see Fig. (6).
2. Long range rapidity fluctuations — *i.e.* positive correlation of the increase of multiplicity in one rapidity interval with the increase of multiplicity several units away.
3. Correlation of the central multiplicity with the multiplicity of neutrons in the neutron detector (most effective for heavy nuclei).

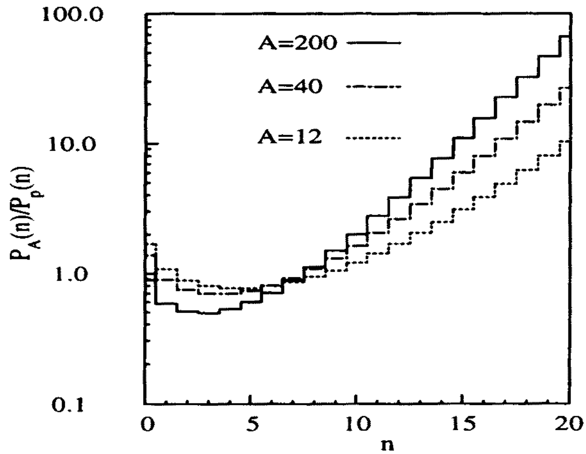

Fig. 6. A-dependence of multiplicity distributions for fixed pseudorapidity interval $0 \leq \eta \leq 2$, and $\langle W \rangle = 100$ GeV.

4.3. Colour transparency phenomena

An important property of QCD is that small objects are expected to interact with hadrons with small cross section [27]. This implies that in the processes dominated by the scattering/production of hadrons in "point-like"(small size) configurations (PLC) when embedded in the nuclei, the projectile or the outgoing hadron essentially does not interact with the nuclear environment [28, 29]. In the limit of colour transparency one expects for an incoherent cross section a linear dependence on A, for example

$$\frac{d\sigma(e + A \to e + p + (A-1)^*)}{dQ^2} = Z \frac{d\sigma(e + p \to e + p)}{dQ^2}, \tag{8}$$

while for coherent processes at $t = 0$ one expects

$$\frac{d\sigma(\gamma^* + A \to X + A)}{dt} = A^2 \frac{d\sigma(\gamma^* + N \to X + N)}{dt}. \tag{9}$$

No decisive experimental tests of this property of QCD were performed so far since in most of the current experiments the energies were not sufficiently high to prevent expansion of the produced small system. The high-energy E665 experiment [30] at FNAL has found some evidence for colour transparency in the ρ meson production off nuclei. However, the data have low statistics, cover a small x, Q^2 range and cannot reliably separate events without hadron production.

A quantitative formulation of colour transparency for high-energy processes can be based on Eq. (3). For the case of nuclear targets it implies that for a small enough colour dipole, the cross section of its interaction with nuclei is proportional to A up to the gluon shadowing factor. As a result the colour transparency prediction for 2 jet and vector meson diffractive production is [31, 32] [4]:

$$\frac{\frac{d\sigma}{dt}(\gamma^* A \to 2jets + A)|_{t=0}}{\frac{d\sigma}{dt}(\gamma^* N \to 2jets + N)|_{t=0}} = \frac{\frac{d\sigma}{dt}(\gamma^* A \to VA)|_{t=0}}{\frac{d\sigma}{dt}(\gamma^* N \to VN)|_{t=0}}$$
$$= \left[\frac{F_A^L(x,Q^2)}{F_N^L(x,Q^2)}\right]^2 = \frac{G_A^2(x,Q^2)}{G_N^2(x,^2Q)} . \tag{10}$$

Gluon shadowing constitutes a rather small effect for $x \sim 10^{-2}$ (see earlier discussion). For smaller x it increases but it is in any case much smaller than the screening effect expected in the case of lack of colour transparency if the produced system interacts with cross section comparable to $\sigma_{\rho N} \sim$ 30-40 mb. For such values of σ one expects the cross section to behave as $\propto A^{4/3}$ for $t = 0$ which would be possible to test using diffractive production by quasi-real photons.

Coherent diffractive ρ,J/ψ-meson production:

The most straightforward test of colour transparency can be made using coherent production of ρ or J/ψ-mesons at small t using nuclei with $A \geq 12$. The p_t resolution of the current detectors is good enough to single out the diffractive peak which is concentrated at $p_t \leq 0.1$ GeV. In the higher x end of the range which could be studied at HERA for vector meson production, $x \sim 10^{-2}$, one expects at large Q^2 nearly complete colour transparency since gluon shadowing effects are rather small and decrease rapidly with increase of Q^2, while the transverse separation,b, between q and $\bar{q}$ is of the order of 0.4 fm for $Q^2 \sim 10$ GeV^2 and further decreases with increase of Q^2 (Fig. 7 [6]). Study of coherent J/ψ meson production would allow to probe colour transparency for propagation of even smaller dipoles since $\langle b_{c\bar{c}}(Q^2 = 0)\rangle \sim 0.2$ fm.

On the other hand as discussed earlier at the smallest values of x of the HERA range, screening effects should start to play a role even at large Q^2 so a gradual disappearance of colour transparency is expected — the emergence of *perturbative colour opacity.* Noticeable screening is expected already on the basis of unitarity constraints. Qualitatively one may expect

[4] In writing Eq. (10) we neglect the difference of Q^2 scales for different processes which is reflected in a different dependence of the essential transverse size of the $q\bar{q}$ state on the process (see Fig. 7). For a discussion of the appropriate scale for dijet production see [33].

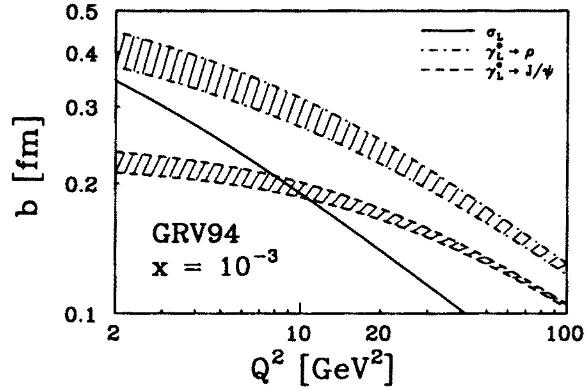

Fig. 7. Average transverse size of the $q\bar{q}$ components effective in $A_{\gamma_L^* N \to VN}$ for ρ– and J/ψ-meson production and σ_L. The probed Q^2 scale is inversely proportional to b^2.

that the rise of the cross section for vector meson production with increasing energy at fixed Q^2 will slow down at significantly lower energies than for the case of the $\gamma^* + p$ reaction. Currently theoretical calculations of vector meson production by transversely Polaris ed photons are difficult because the nonperturbative large distance contribution is not as strongly suppressed in this case as in the longitudinal case. If contribution of pairs with large transverse size is indeed important for σ_T, it would be filtered out with increasing A leading to larger values of σ_L/σ_T for large A.

Let us enumerate several other effects of Colour Transparency (CT) in diffractive production.

1. Production of excited vector meson states ρ', ϕ'.

   In the CT limit, QCD predicts a universal A-dependence of the yields of the lowest mass and excited states (this includes the effect of gluon shadowing in Eq. (10)). This is highly nontrivial since the sizes of the excited states are much larger, so one might expect larger absorption. On the other hand, for lower Q^2 average transverse distances, b, are not small. At these distances the wave functions of ground and excited states differ. So in this Q^2 range the relative yields of various mesons may depend on A.

2. Production of high p_t dijets.

   The uncertainty relation indicates that coherent production of dijets with large p_t, carrying all the momentum of the diffractively produced system is dominated by distances $r_t \propto \frac{1}{p_t}$. Hence filtering out of soft jets is expected, leading to a broadening of the p_t and thrust distributions. At the same time the study of the A-dependence of low p_t jets would allow to address the question of colour opacity. Another feature to look for would be the distribution over the electron-two jet plane angle as suggested in [34].

3. Coherent diffractive production at $-t \geq 0.1$ GeV^2 for $A = 2, 4$.

   An important question here is the possibility to observe the "disappearance" of colour transparency for ρ-meson production and the emergence of "colour opacity" — due to nonlinear screening effects at $x \sim 10^{-4}$. Manifestations of CT would be the increase of the differential cross section $\frac{d\sigma}{dt}$ below the diffractive minimum ($|t_{\min}(^4He)| \approx$ 0.2 GeV^2 and suppression of the cross section in the region of the secondary maximum. A gradual disappearance of CT in this region with increasing energy would appear as a very fast increase with energy of the secondary maximum of the t distribution. Remarkably, in this region the cross section for the process is proportional to $[G_N(x, Q^2)]^4$, where G_N is the gluon density in the nucleon [35, 36]. The present HERA beam optics would allow measurements of quasielastic processes with ^{4}He in the region of the secondary maximum ($|t(^4\mathrm{He})| \approx 0.4$ GeV^2). For a luminosity of 10 pb^{-1} it would be possible to measure the ρ-meson production cross section up to $Q^2 \sim 10$ GeV^2.

4. A-dependence of rapidity gaps between jets in photoproduction.

   Recently photoproduction events which have two or more jets have been observed in the range $135 < W_{\gamma p} < 280$ GeV with the ZEUS detector at HERA. A fraction of the events has little hadronic activity between the jets. The fraction of these events, $f(\Delta\eta)$, reaches a constant value of about 0.1 for large pseudorapidity intervals $\Delta\eta \geq 3$. The observed number of events with a gap is larger than that expected on the basis of multiplicity fluctuations assuming the exchange of a colour singlet. This value is rather close to estimates in perturbative QCD neglecting absorptive effects due to interactions of spectator partons. It is much larger than the values reported by D0 and CDF. Small effects of absorption are by no means trivial in view of the large interaction cross section for many components of the hadronic wave function of the real photon. They may indicate that colour transparency is at work here as the ZEUS trigger may select point-like configurations in the photon wave function [37]. To check this idea it would be natural to study the A-dependence of rapidity gap survival. It is demonstrated in [37] that this probability strongly depends on the effective cross section of the interaction of the photon with the quark–gluon configurations involved in producing rapidity gap events. One would be sensitive to cross sections as small as ~ 5 mb.

5. Real photon–nucleus scattering

Since coherent lengths in high-energy processes are large, a fast hadron can be considered as a superposition of frozen constituents. Therefore the existence of parton configurations within hadrons having small interaction cross section, *i.e.* small size (as confirmed by the diffractive electroproduction of ρ-meson) implies that various configurations in the projectile should interact with the target with significantly different strengths. It is convenient to introduce a bulk characteristic of these fluctuations of the strength of interactions — the probability for a hadron to interact with a certain cross section σ, $P_{hN}(\sigma)$, see review in [38]. One can relate the cross sections of coherent diffractive processes off protons and nuclei to the moments of $P_{hN}(\sigma)$: $\langle\sigma^n\rangle = \int \sigma^n P_{hN}(\sigma) d\sigma$. For example, the ratio

$$\sigma_{\rm eff} \equiv \frac{\langle\sigma^2\rangle}{\langle\sigma\rangle} \tag{11}$$

is related both to the value of the ratio between $d\sigma(h+N \to X+N)/dt$ and $d\sigma(h+N \to h+N)/dt$ for diffractive inelastic and elastic production at $t=0$, and to the amount of nuclear shadowing in hD scattering. The value of $\sigma_{\rm eff}$ increases significantly with energy. Based on the data of [39], we find $\sigma_{\rm eff}(\langle W\rangle = 15\ {\rm GeV}) \approx 23 \pm 2$ mb, while at HERA energies this parameter is much larger $\sigma_{\rm eff}(\langle W\rangle = 150\ {\rm GeV}) \approx 38 \pm 4$ mb based on the data of H1 [15]. Therefore a significant increase of nuclear shadowing between fixed target energies is expected at HERA. Besides, as we already indicated in Section 3, since $\sigma_{\rm eff}$ at HERA is much larger for real photons than for DIS, the nuclear shadowing for real photons is expected to be significantly larger than at $Q^2 \geq$ few GeV^2.

The behaviour of $P_{hN}(\sigma)$ in the limit of small σ is determined from perturbative QCD:

$$P_{hN}(\sigma)_{\sigma\to 0} \propto \sigma^{n-2}, \tag{12}$$

where n is the number of valence quarks in hadron h. From the analysis of diffractive hp and hD data and Eq. (12), it was concluded that $P_{hN}(\sigma)$ for $h = \pi, N$ is very broad, see Fig. 8. This observation was further supported by the studies of diffraction off heavier nuclei [38].

The study of $P_{\gamma N}(\sigma)$ is of special interest because unlike in the hadron case, $P_{\gamma N}(\sigma) \propto \sigma^{-1}$, for $\sigma \to 0$ while for large σ it should resemble that of the pion — due to the vector meson contribution. So the theoretical

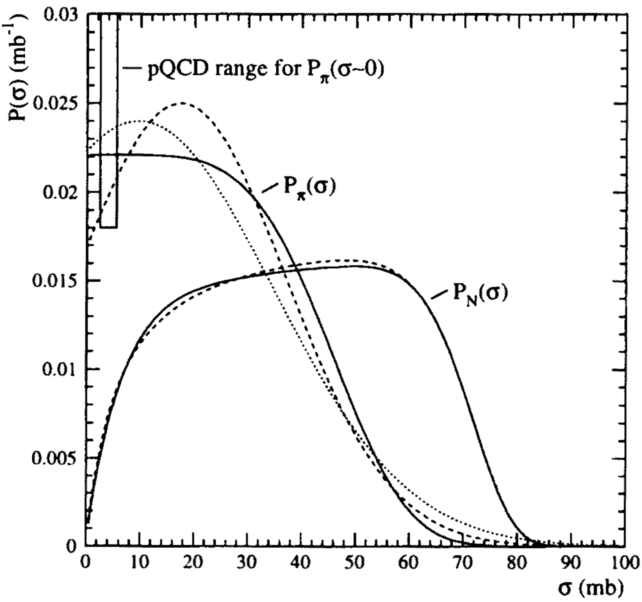

Fig. 8. Cross-section probability for pions $P_\pi(\sigma)$ and nucleons $P_N(\sigma)$ as extracted from experimental data. $P_\pi(\sigma \sim 0)$ is compared with the perturbative QCD prediction.

expectation is that $P_{\gamma N}(\sigma)$ is even broader than for pions. It would be important to check this experimentally with systematic studies of diffraction off a set of nuclei and with measurements of the total cross sections of γA scattering. The challenging questions include

- Does shadowing really increase with energy, or it saturates? The increase of σ_{eff} indicates that shadowing will continue growing up to HERA energies.
- Is there a smooth transition between shadowing for real photons and for $Q^2 \sim$ few GeV^2 for the same W? The much smaller value of σ_{eff} for DIS (Eq. (6)) indicates that shadowing for the real photon case would be substantially larger.
- How far is the ratio $\frac{\sigma_{\text{diff}}(\gamma A)}{\sigma_{\text{tot}}(\gamma A)}$ from the black body limit for large A?
- A-dependence of dijet production in diffractive events.
- What is the effective cross section determining coherent production of ρ and ϕ-mesons — does the vector dominance model (VDM) work in this new energy domain? Is the ρ-N total cross section really ≈ 40 mb at HERA energies as VDM and HERA $\gamma + p \to \rho + p$ data imply?

- How different would the A-dependence of ρ and ρ'-meson coherent production be ? This may be a sensitive way to investigate nondiagonal transitions in soft diffraction.
- Color opacity — Are there ways to select configurations in the photon which interact with cross section exceeding that of ρN scattering?
- A-dependence of charm production in diffraction and in total cross sections.

6. Connection to heavy-ion collisions at high energies

The interplay between the physics which can be studied in high-energy eA collisions at HERA and that to be studied in the heavy ion physics was discussed at the dedicated workshop "Nuclei at HERA and Heavy Ion Physics" which was held at Brookhaven National Laboratory in 1995. It was concluded that the measurements of eA collisions at HERA can provide crucial information necessary for unambiguous interpretation of the heavy ion collisions at RHIC and LHC for establishing whether a quark–gluon plasma is formed in these collisions.

Three major links are

• *Nuclear gluon shadowing*

One needs $xg_A(x,Q^2)$ for $x \sim 10^{-2}$, $Q^2 \sim$1–10 GeV^2 and $x \sim 10^{-3}$, $Q^2 \sim$ 10 GeV^2 to fix the initial conditions at RHIC and LHC respectively. This is especially important for the LHC since mini-jet production determines the initial conditions for $\sqrt{s} \geq$ 100GeV $\dot{A}$. The bulk of the particles produced at central rapidities in AA collisions at the LHC is expected to be generated due to this mechanism [41]. Currently uncertainties in nuclear shadowing transform into at least a factor 2–4 differences in the final transverse energy flow [40].

• *Jet quenching*

Recent QCD studies [42] have demonstrated that the medium induced energy losses and p_t broadening of a high energy parton traversing a hot QCD medium are much larger than in the case of a cold medium. This provides a unique new set of global probes of the properties of the state formed during AA collisions [40]. To interpret unambiguously this effect it is necessary both to measure the nuclear gluon shadowing and to study the parton propagation in cold matter in DIS to confirm that the energy losses (p_t-broadening) remain small at energies comparable to those to be studied at RHIC and LHC.

• *Testing of soft dynamics of interactions with nuclei*

Study of eA interactions at HERA in **the same energy range** as that to be studied in pA and AA collisions at RHIC ($\sqrt{s} \sim$ 200 GeV) will provide a unique testing ground for the modern models of interactions with nuclei which aim at describing on the same footing ep, eA, pp, pA, AA collisions [43]. It would allow to be established whether or not the same dynamics determines hadroproduction in eA collisions and in central AA collisions.

I would like to thank all my colleagues in working group 8 of the workshop "Future of HERA" for their invaluable assistance and for numerous discussions. My special thanks are to A. Bialas with whom we collaborated on writing the theoretical part of the report. I thank the U.S. Department of Energy for financial support under grant number DE-FG02-93ER-40771.

REFERENCES

[1] M. Arneodo, A. Bialas, W. Krasny, T. Sloan, M. Strikman, Report of conveners of the working group "Light and Heavy Nuclei", Proceedings of workshop "Future of HERA" in press; http://www.desy.de/ heraws96/proceedings.

[2] V.N. Gribov, *Zh. Eksp. Teor. Fiz.* **57**, 1309 (1969) [*Sov. Phys. JETP* **30**, 709 (1970)].

[3] J.D. Bjorken in Proceedings of the International Symposium on Electron and Photon Interactions at High Energies, p. 281, Cornell (1971).

[4] R. Baier, Yu.L. Dokshitzer, A.H. Mueller, S. Peigné, D. Schiff, hep-ph 9608322.

[5] B. Blättel, G. Baym, L.L. Frankfurt, M. Strikman, *Phys. Rev. Lett.* **71**, 896 (1993).

[6] L. Frankfurt, W. Koepf, M. Strikman, *Phys.Rev.* **D54**, 3194 (1996).

[7] A.H. Mueller, J-W.Qiu, *Nucl. Phys.* **B268**, 427 (1986).

[8] L.L. Frankfurt, M. Strikman, *Phys. Rep.* **160**, 235 (1988).

[9] L. McLerran, R. Venugopalan, *Phys. Rev.* **D50**, 225 (1994).

[10] V.N. Gribov, *Zh. Eksp. Teor. Fiz.* **56**, 892 (1969).

[11] V. Abramovskiĭ, V.N. Gribov, O.V. Kancheli, *Sov. J. Nucl. Phys.* **18**, 308 (1974).

[12] L.L. Frankfurt, M.I. Strikman, *Nucl. Phys.* **B316**, 340 (1989).

[13] B.Z. Kopeliovich, B. Povh, *Phys. Lett.* **B367**, 329 (1996).

[14] B.K. Jennings, G.A. Miller, *Phys. Rev.* **C49**, 2637 (1994).

[15] H1, S. Aid *et al.*, *Z. Phys.* **C69**, 27 (1995).

[16] NMC, P. Amaudruz *et al.*, *Nucl. Phys.* **B371**, 553 (1992).

[17] L. Frankfurt, M. Strikman, *Phys. Lett.* **B382**, 6 (1996).

[18] T. Gousset, H.J. Pirner, *Phys. Lett.* **B375**, 354 (1996).

[19] L. Frankfurt, M. Strikman, S. Liuti, *Phys. Rev. Lett.* **65**, 1725 (1990).

[20] J.W. Qiu *Nucl. Phys.* **B291**, 746 (1987).

[21] L. Frankfurt, M. Strikman, S. Liuti, *Proceedings of the Conference on Particles and Nuclei XIII, Perugia, Italy (1993)*, ed. A. Pascolini, World Scientific Singapore 1993, p.342.

[22] K.J. Eskola, *Nucl. Phys.* **B400**, 240 (1993).

[23] K.J. Eskola, Jian-wei Qiu, Xin-Nian Wang, *Phys. Rev. Lett.* **72**, 36 (1994).

[24] N.N. Nikolaev, V.G. Zakharov, *Z. Phys.* **C49**, 607 (1991).

[25] A. Donnachie, P. Landshoff, *Phys. Lett.* **B296**, 227 (1992).

[26] H. Abramowicz, J. Bartels, L. Frankfurt, H. Jung, Diffractive Hard Scattering: Summary Report of the Working group, Proceedings of workshop "Future of HERA" in press; http://www.desy.de/ heraws96/proceedings.

[27] F.E. Low, *Phys. Rev.* **D12**, 163 (1975).

[28] S.J. Brodsky *Proceedings of the Thirteenth International Symposium on Multiparticle Dynamics*, ed. W. Kittel, W. Metzger and A. Stergiou, World Scientific, Singapore 1982, p.963.

[29] A.H. Mueller *Proceedings of the Seventeenth Rencontre de Moriond, Moriond, 1982*, ed. J. Tran Thanh Van, Editions Frontieres, Gif-sur-Yvette, France 1982, Vol. I, p.13.

[30] M.R. Adams *et al.*, *Phys. Rev. Lett.*, **74**, 1525 (1995).

[31] L. Frankfurt, G.A. Miller, M. Strikman, *Phys. Lett.* **B304**, 1 (1993).

[32] S.J. Brodsky, L. Frankfurt, J.F. Gunion, A.H. Mueller, M. Strikman, *Phys. Rev.* **D50**, 3134 (1994).

[33] J. Bartels, H. Lotter, M. Wusthoff, *Phys. Lett.* **B379**, 239 (1996).

[34] J. Bartels, C. Ewerz, H. Lotter, M. Musthoff, DESY 96-085.

[35] H. Abramowicz, L. Frankfurt, M. Strikman, DESY-95-047; SLAC Summer Inst. 1994:539-574.

[36] L. Frankfurt, W. Koepf, M. Sagrsyan, M. Strikman, Color transparency and color opacity in coherent production of vector mesons off light nuclei at small x, nucl-th/9608492, to be published in the proceedings of the HERA workshop.

[37] L. Frankfurt, M. Strikman, Possible evidence for color transparency from dijet production with large rapidity gaps in γ p scattering at HERA and how to test it in γ A scattering, hep-ph/9609456, to be published in the proceedings of the HERA workshop.

[38] L.L. Frankfurt, G.A. Miller, M. Strikman, *Annu. Rev. Nucl. Part. Sci.* **44**, 501 (1994).

[39] T.J. Chapin *et al.*, *Phys. Rev.* **D31**, 17 (1985).

[40] M. Gyulassy, Proc. 'Nuclei at HERA and Heavy Ion Physics', BNL-62634, 1995.

[41] X-N. Wang, M. Gyulassy, *Phys. Rev. Lett.* **68**, 1480 (1992).

[42] R. Baier, Yu.L. Dokshitzer, A.H. Mueller, S. Peigné, D. Schiff hep-ph 9607355.

[43] K. Geiger, Contribution to the HERA workshop proceedings; J. Ellis, K. Geiger, H. Kowalski, to be published in *Phys. Rev.* **D**, e-Print Archive: hep-ph/9605425.