Possibility of antiscreening effect in the scattering of high-energy leptons by nuclei

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The scattering of leptons by nuclei in the deep-inelastic region is considered within the framework of the parton model. It is shown that at $x \approx x_0 \approx 0.5$–$0.1$, the parton model leads to a unique antiscreening effect, i.e., the cross section for the interaction with the nucleus exceeds the sum of the cross sections for interaction with the nucleons making up the nucleons by about 10%. It is shown that in the integral total cross section the effects of diffraction scattering and antiscreening should cancel out so that, e.g., the total cross section for the scattering of a neutrino by a nucleus is equal to the sum of the cross sections for the interaction with the nucleons.

We consider in this article deep inelastic scattering of leptons by nuclei, and are interested mainly in the region of diffraction scattering. This question has already been considered in a number of papers (see[1–3] and the references therein). An analysis has shown[4] that it is impossible to explain theoretically the experimentally observed[5] rapid decrease of the screening effect with increase of the square of the momentum transfer Q^2.

We shall show that the parton model in the form developed by Gribov[6,7] and Kancheli[8] provides a natural explanation for this phenomenon. Namely, whereas for very small values of the scaling variable $x = Q^2/2m_N\nu$ the parton model leads to the usual diffraction description with screening of the nucleons in the nucleus, at large values of x the parton predicts an appreciable (on the order of ten per cent) increase of the cross section for the interaction with the nucleus over the sum of the cross sections for the interaction with the nucleons making up the nucleus (antiscreening). This effect can explain the failure to observe screening in experiment as a manifestation of a transition from screening at $Q^2 = 0$ to antiscreening at $Q^2 \gg 1$ GeV^2 (electro-production was investigated experimentally at $Q^2 \approx 1$ GeV^2 [5]).

Moreover, it is to be expected that the effects of screening and antiscreening cancel each other in the integral total cross section:

$$\int_0^1 F_i^{lA}(x)\,dx = Z\int_0^1 F_i^{lp}(x)\,dx + (A-Z)\int_0^1 F_i^{ln}(x)\,dx, \qquad (1)$$

where A is the atomic number of the nucleus and Z is the charge of the nucleus, F^{lA}, F^{lp}, and F^{ln} are the structure functions for the interaction of the lepton with the nucleus, proton, and neutron, respectively. For neutrino and antineutrino reactions, the sum rule (1) denotes that the cross section for the interaction with the nucleus is simply the sum of the cross sections for the interaction with the individual nucleons.

The scattering of a virtual photon by a nucleus is best considered in the Breit coordinate system, where the photon energy is equal to zero. In this coordinate system the nucleus is characterized by a system of partons,

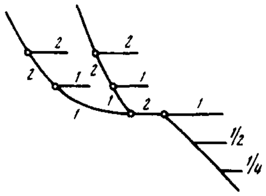

FIG. 1.

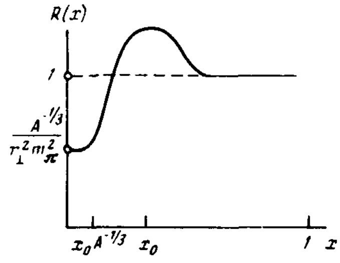

FIG. 2.

each of which carries some fraction of the longitudinal momentum, which we shall refer to the momentum of one nucleon. The photon in the Breit system of coordinates interacts with a parton of momentum $\sqrt{Q}/2$.

The central question is whether this parton belongs to an individual nucleon or to an assembly of nucleons. The nucleons are separated from each other by distances on the order of $1/m_\pi$ in the lab, and by distances on the order of $m^{-1}m_N p^{-1}$ in the Breit system. On the other hand, a parton with momentum px has a longitudinal dimension on the order of $\Delta Z \approx 1/px$.

We see that partons with values of x on the order of

$$x \lesssim x_0 \approx m_\pi/m_N, \qquad (2)$$

and belonging to nucleons with the same transverse coordinates are in fact situated in one region of space and can interact strongly with one another. The main hypothesis of the parton model is that the interaction establishes a certain universal parton-momentum distribution.[7,8] In the language of the perturbation-theory diagrams, this phenomenon is manifest in a coalescence of short parton ladders from different nucleons, and leads to a decrease of the parton density below the coalescence point.

At $x \lesssim x_0 A^{-1/3}$, the partons of all $n \approx r_\perp^2 m_\pi^2 A^{1/3}$ nucleons of the nucleus, contained in a tube of cross section $\sigma \approx \pi r_\perp^2$ coalesce ($r_\perp$ is the radius of the nucleon and $r_\perp^2 m_\pi^2 \approx 0.3-0.5$). As a result, at $x \lesssim x_0 A^{-1/3}$ the parton density decreases in proportion to $A^{-1/3}$.

The coalescence of the partons from different nucleons leads to the same effects as diffraction scattering. Indeed, the photon interacts with the high-energy partons, the number of which is proportional to $A^{2/3}$. For this reason, the interaction cross section is proportional to $A^{2/3}$ at low values of the scaling variable x. This diffraction prediction is shared by the parton model with practically all the approaches proposed to date. A more specific prediction is that of the dominance of the scattering cross section of transversely polarized photons also in the diffraction region, a prediction that follows from the assumption that the partons have spin $\frac{1}{2}$. At first glance it is more natural to expect independence of the cross section of the polarization in diffraction scattering.

An important circumstance is that the coalescence does not change the total momentum of the partons. The momentum is only redistributed among partons with different values of x. On the other hand, the deep-inelastic scattering is determined precisely by the partons' share of the momentum. We thus arrive at the sum rule (1) and at the conclusion that the screening of the nucleons at very small values of x should be accompanied by antiscreening at large values of x.

The appearance of antiscreening can be easily traced with the multiperipheral parton wave functions of the nucleus as an example. Figure 1 shows the coalescence of the parton ladders in a theory of the $\lambda\phi^3$ type. If two partons with unity momenta (in arbitrary units) coalesce, then we have double the parton density at momenta larger than unity, a single density at momenta smaller than unity, and three partons with momentum equal to unity.

This leads to form of the ratio $R(x)$ shown in Fig. 2 for the density of the partons in the nucleus to the sum of the densities of the partons and of the nucleons making up the nucleus. The quantity $R(x)$ should have a maximum at the coalescence point at $x \approx x_0$, and the width of the maximum is determined by the radius of the short-range rapidity correlations and should be of the order of x_0. According to the estimate (2), $x_0 \approx 0.05$ to 0.1. Since the structure functions are already practically constant at $x \sim x_0$, we have approximately $\int_0^1 R(x)\,dx \approx 1$, i.e., the area of the excess of $R(x)$ over unity should equal to area between $R(x)$ and unity in the screening region. It follows that the antiscreening effect should be on the order of ten percent.

At the presently attainable electron energies, it seems that observation of the antiscreening effect and verification of sum rule (1) are both feasible. A confirmation of these predictions would be of interest not only in itself, but also in connection with the consequences that it would yield for the parton model. Both antiscreening and screening are possible in the parton model only in the presence of coalescence of the parton ladders. We recall in this connection that it is precisely the coalescence of the parton ladders which is the mechanism that leads to the prediction that the total cross sections for interaction with different hadrons are equal at asymptotically high energies.[7,9] What is important is that in hadron reactions these coalescence effects become significant only at ultrahigh energies, when $\ln E/m \sim 10-40$. At the same time, in deep-inelastic scattering by nuclei the existence of coalescence of parton ladders can be explained already at the presently accessible energies on the order of several dozen GeV.

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