IN SEARCH FOR (QUANTUM) COLOR TRANSPARENCY

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ABSTRACT

Color transparency (CT) is an effect of suppression of nuclear shadowing of hard reactions, closely related to the color screening. A brief review of theoretical development and experimental search for CT, failed and successful, are presented. A special emphasis is made on a quantum-mechanical nature of CT, as opposed to a wide spread erroneous classical treatment of this phenomenon. The typical predictions of the classical approach, all contradicting quantum mechanics are:
- factorization of cross section of hard reactions on a nucleus;
- ”nuclear transparency”, a normalized ratio of nuclear to nucleon cross sections, cannot exceed one;
- the larger is a radius of a hadron, the stronger it attenuates in a nucleus;
- the higher is the energy of hadrons participating in a hard reaction, the less is the nuclear attenuation;
- due to CT hard processes provide a better opportunity to study Fermi-momentum distribution, than soft reactions; etc.

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1 Quantum approach versus vulgar (classical) treatment of Color Transparency.

Nuclei are unique analyzers of the space-time evolution of strongly interacting hadronic system at early stage of their development of about a few fermi’s. Specifically, a nucleus can play a role of a detector of the size of the ejectile (sometimes of the projectile as well) emerging from a reaction on a bound nucleon. Of special interest are the exclusive reactions, where any soft inelastic final (initial) state interaction looks like an absorption of the hadron, which we are tracing on. The smaller is the size of the wave packet, the weaker it interacts, the more transparent is the nuclear matter. It is a direct consequence of color screening: a colorless object can interact only due to a transverse distribution of hidden color. The cross section vanishes as a square of the color dipole momentum of the state. Another important condition is a sufficiently high energy of the ejectile to ”freeze” its transverse size while it is passing through the nucleus. We will be back to this question later.

The phenomenon of suppression of nuclear shadowing in some reactions due to the color screening is called color transparency (CT). It was first demonstrated in diffractive processes [1, 2] and suggested in quasielastic scattering [3, 4].

One of the goals of the present talk is to give a brief review of theoretical development and results of experimental search for CT. The another is to emphasize the importance of quantum-mechanical approach to CT, as distinct from a vulgar treatment of this phenomenon, which is unfortunately wide spread. The latter is probably because human intuition prefers a simplification towards the classical understanding. We are discussing it below, but here there are a few typical examples of misuse of such simplifications (one can find more in [5]):

- **Factorization.** *It is assumed that the cross section, \( \sigma_A \), of a hard process on a nucleus factorizes to the cross section on a bound nucleon, \( \sigma_N \), and a survival probability of participating hadrons to traverse the nucleus without interaction,*

  \[
  Tr = \frac{\sigma_A}{A \sigma_N} \tag{1}
  \]

  *The quantity \( Tr \) is usually called nuclear transparency.*

  A quantum-mechanical interference, however, strongly violates the factorization. We give below a few explicit examples [6, 7, 8], when the transparency (1) exceeds unity, what would be impossible, if \( Tr \) indeed were a transparency.
• **Space-time evolution of ejectile.** Classical approach operates with fixed, average sizes of an initial state, produced in a hard process, and a final hadron. It is assumed that quarks propagate along fixed trajectories with separation increasing as a linear or square root function of time. The latter is called sometimes "quantum expansion" or "quantum diffusion". Despite the fancy use of the word "quantum", this approximation misses all known quantum-mechanical effects. It predicts: i) that nuclear transparency \( I \) is always less than unity; ii) the larger is the hadronic radius, the stronger is the nuclear attenuation; iii) nuclear attenuation decreases with energy, since the expansion slows down due to Lorentz time delay; etc.

These expectations based on the classical treatment of the evolution, fail in many cases, if one compare them with results of correct quantum mechanical calculations. One should use wave functions of initial and final states, rather than average radiuses, and sum over different quark trajectories [10, 6, 7].

• **Color filtering.** This means that large-separation components of a wave packet propagating in a nuclear matter are filtered out due to a stronger attenuation. The classical approach is principally unable to incorporate this effect, because it ignores the distribution over the transverse separation in the wave packet.

Properly taken into account, the color filtering leads to salient predictions. It makes a nuclear matter much more transparent [1], and increases transverse momenta of particles produced in diffractive dissociation [2]. The filtering changes the form of the wave packet, what results in a nuclear antishadowing in some channels [3, 4, 5].

• **Fermi motion in \( A(e,e'p)A' \).** There is a wide spread opinion, that quasielastic electron scattering at high \( Q^2 \) is a precise tool for study Fermi distribution in nuclei. It is based upon the classical treatment of CT and of the evolution as well. The idea is, that the final state interaction vanishes at high \( Q^2 \), and the recoil proton carries an undistorted information about its initial Fermi momentum.

A quantum-mechanical consideration of CT [8] in hadronic basis shows that in this specific reaction CT is possible only due to the Fermi motion. Different components of the nuclear wave function add up to create a small-size wave packet, eliminating a certainty in an initial Fermi momentum of the proton. Besides, this wave packet producing a proton in the final state, transfers to the nuclear matter during passing it a negative longitudinal
momentum of uncertain amount. The same concerns the wide-angle quasielastic proton scattering.

2 Space-time evolution

The problem of evolution of a wave packet in nuclear environment is of great importance, and probably is the most complicate one. There are known a few approaches. The first one, exploring the connection of the hadronic basis with eigenstates of interaction, was suggested in 1980 [11]. It was also noticed in the first paper on CT [1], that CT is a particular case of Gribov’s inelastic corrections [12]. Later the connection with the hadronic basis was explored also in [13, 14].

If one decomposes an ejectile wave packet over the complete set of hadronic states, one should sum all over the amplitudes of hard production of these states, including all possible diagonal and off diagonal diffractive rescatterings in the nucleus. It is very difficult problem. An effective approach to this difficult problem, an approximation of diffractive matrix, was suggested recently in [15].

In the hadronic representation the violation of the factorization is quite natural: one should compare a hard production of a proton on a free proton target, with production of different excited states on a bound proton.

It is possible to study the evolution in the quark representation as well, but one has to take into account propagation of the quarks over all possible trajectories, weighted with appropriate factors. It was done in [10, 6, 7] using the path integral technique.

3 Diffraction on nuclei

Nonexponential attenuation. The effect of high nuclear transparency originating from the color screening was first claimed in [1]. The amplitude of probability of passing a nucleus of thickness $T$ reads,

$$F = \langle f | e^{-\frac{1}{2} \sigma(\rho^2) T} | i \rangle_{\rho}$$

Here $|i\rangle$ and $|f\rangle$ are initial and final state wave functions. The interaction cross section of $q\bar{q}$ pair with transverse separation $\rho$ behaves like $\sigma(\rho) \propto \rho^2$ at $\rho \to 0$ due to the color screening.

In the limit $T \gg 1 \, fm^{-2}$ expression (3) gives $F \propto 1/T$. This nonexponential attenuation results from presence in the wave packet a penetrating component with small $\rho$. The same
component, filtered out by the nucleus, provides a broadening of transverse momenta of hadrons produced in diffractive dissociation [2].

These manifestations of CT are completely lost in the classical approach.

Diffractive virtual photoproduction of vector mesons on nuclei. This process is a perfect laboratory for study of CT. The qualitative space-time pattern of it was discussed in [10], and a detailed analyses was undertaken in [3, 17, 7]. The main observations are:

Nuclear antishadowing, \( T_r > 1 \), of production of radial excitations, \( \Psi' \) and \( \rho' \) at small \( Q^2 \) [6, 7]. This is a direct consequence of the color filtering. Indeed, these states have a small overlap with a quark component of a photon due to a node in the wave functions \( \Phi_{V'}(\rho) \). The nuclear filtering squeezes the passing wave packet, and can substantially increase the overlap with \( \Phi_{V'}(\rho) \).

\( Q^2 \)-dependence of nuclear transparency for \( \Psi' \) and \( \rho' \) production is shown in fig.1 [7]. The antishadowing at small \( Q^2 \) changes to an universal approach from below to \( T_r = 1 \) at high \( Q^2 \).

It was predicted in [6], that, contrary to the naive expectation, the nuclear transparency in diffractive photoproduction of vector mesons decreases at high energies. This is a consequence of the growth of the coherence length, resulting in a longer path inside the nucleus covered by the quark fluctuation of the photon. This prediction was confirmed by measurements of the NMC collaboration in a good agreement with calculated energy dependence [17].

The diffractive photoproduction of vector mesons provides unique information about their wave functions. Indeed, varying \( Q^2 \), one scans the wave function of the final meson, changing the range of impact parameter \( \rho \), where the wave function of the \( q\bar{q} \) wave packet and \( \Phi_{V'}(\rho) \) overlap [7].

4 Quasielastic scattering

Electron scattering \( A(e,e'p)A' \). As distinct from the diffraction, it is not so easy to produce in this process a small-size wave packet, consisted of many states, \( p, p^*, p^{**} \ldots \). It is impossible at all on a free proton target, because the mass of the ejectile is strongly correlated with value of Bjorken variable, \( x_B = Q^2 / 2m_p\nu \), fixed by the electron momenta. One knows, however, that in quantum mechanics a detector affects the result of measurement. It is just the case: putting a detector of size of the ejectile (rescattering on other nucleons) close to the target proton, one cannot more consider the latter as being at rest (Fermi motion), due to the uncertainty principle. (Fermi motion). As a result the mass of ejectile acquires an uncertainty too, and a wave packet of
a definite size can be produced. However the mass spectrum of is restricted by the available Fermi momenta, and depends on the value of $x_B$. Varying the latter, one changes the amount of CT: $Tr$ increases at $x_B < 1$ (positive missed momenta) and even exceeds one. On the contrary, $Tr$ falls down at $x_B > 1$ approaching the expectation of the Glauber approximation. Results of calculations [8] in a simple two channel model, with $m = m_p, m^* = 1.6 GeV$, are shown in fig.2 vs $Q^2 = 7, 15, 30 GeV^2$. We predict very weak effect around $x_B = 1$ at $Q^2 = 7 GeV^2$, in agreement with the results of recent measurements at SLAC. The effect might be even overestimated by this model. It was argued in [15], using more developed model, that the initial size of the produced wave packet only slowly decreases with $Q^2$.

Note that due to this uncontrolled Fermi bias of $Tr(x_B)$, CT doesn’t help, but spoils any opportunity to measure the large momentum tail of Fermi distribution, even on light nuclei. It is better to do at small $Q^2$. The same is true for the process which follows.

Wide angle $A(p,2p)A'$ scattering. The Fermi bias of nuclear transparency might be closely relevant to the puzzling results of search for CT in Brookhaven experiment [18]: nuclear transparency unexpectedly falls down the value corresponding to Glauber approximation, at incident momenta above 10 GeV/c. The measurements were performed at three beam momenta, 6, 10 and 12 GeV/c, and distributed over missed (“Fermi”) momenta. The effect of Fermi bias just causes the decreasing dependence of $Tr$ on the c.m. total energy, which was observed at beam momentum 12 GeV/c. Numerical estimations with the same simple model are compared with the data [18] in fig.3. The interval of masses $m^* = 1.5 – 1.8 GeV$ was used. At lower beam momentum the effect is weaker due to a faster evolution. The calculations essentially underestimate only one point in fig.3b. Otherwise the data do not contradict the model, though the latter is oversimplified.

5 Observed signals of CT

Quasifree charge-exchange scattering. In quasielastic scattering presence of Landshoff-type graphs suppresses CT signal up to very high $Q^2$, when Sudakov form factor becomes important. In the reaction of charge-exchange scattering the Regge poles are known to dominate at low transferred momenta $q^2$, what provides a formfactor-type vertex. At higher values of $q^2$ Regge cuts, containing Landshoff-type graphs, become important. Destructive interference pole-cut manifests as a minimum in $q^2$-dependence of differential cross section. For instance in reaction $\pi^- p \rightarrow \pi^0 n$ it occurs at $q^2 \approx 0.6 GeV^2$. Hence at $q^2 < 0.5 GeV^2$ one can believe in the pole
dominance.

Without Landshoff graphs the hadron formfactor squeezes the hadron to a small size even at quite low $q^2$. Indeed the form factor provides a size $\rho^2 \sim 1/q^2$, as compared with average hadronic dimension $\rho^2 \sim m_{\pi}^2$. So the absorption cross section of such a wave packet is suppressed by a factor of the order of $m_{\pi}^2/q^2$, what is enough to make a nucleus transparent already at $q^2 > 0.2 \, GeV^2$. So we have a gap $0.2 < q^2 < 0.5 \, GeV^2$, where a strong CT effect could be expected.

Result of calculations [19, 10] are compared with data [20] in fig.4 Multiple elastic rescatterings were included, because the recoil neutron escaped detection. Calculations were performed in the standard Glauber approximation and including CT effect. One can see that the data strongly support the latter variant.

Note that strong CT effect predicted and observed in Regge-exchange amplitude, should result in a nuclear enhancement of polarization in a quasielastic scattering. Indeed, at high energies polarization is suppressed by smallness of a spin-flip amplitudes, dominated by Regge-exchange. On a nucleus the latter is enhanced, but the Pomeron, non-flip part not. So the ratio of nuclear to nucleon polarizations is rising function of $Q^2$. On heavy nuclei this ratio exceeds factor of 2 at $Q^2 \approx 1 \, GeV^2$ [19].

Inclusive hadron production in deep inelastic scattering. CT effects are not restricted only by exclusive processes. They might be important also in inclusive reactions, at least at a kinematic border, towards the exclusive limit.

High nuclear transparency, $Tr \approx 1$ was observed by EM collaboration [22] at high energies. Calculations [21], taking into account a formation zone of particle production and CT effect nicely agree with the data, shown in fig.5 One can see that without CT effects theory substantially underestimates the data.

6 Conclusion

This short talk was aimed to the emphasis of the quantum mechanical nature of the CT phenomenon as opposed to the wide spread classical interpretation. One can find more about this in reviews [23, 9].
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Figure captions

Fig.1 Nuclear transparency for Ψ′ and ρ′ electroproduction on Fe as function of $Q^2$.

Fig.2 Nuclear transparency in $(e, e'p)$ reaction on Fe as function of $x_B$. Curves, long-dashed, solid and short-dashed, correspond to values of $Q^2 = 7, 15$ and $30 GeV^2$ respectively.

Fig.3 Comparison with data [18] at beam momenta 6 (a), 10 (b) and 12 (c) GeV/c. At each beam momentum the points are distributed over the missed momentum as it is explained in [18]. Calculations are performed in the simplest two-channel model with $m^* = 1.5 GeV$ (dashed curve), and $m^* = 1.8 GeV$ (solid curve).

Fig.4 Nuclear transparency of reaction $\pi^- C^{12} \rightarrow \pi^0 X$ as function of the momentum transfer squared $q^2$. Data at 40 GeV/c are from [20]. The dashed curve is the result of Glauber approximation. The solid curve incorporates with CT.

Fig.5 Nuclear transparency in the inclusive electroproduction of hadrons, $eA \rightarrow e'hX$, at $\langle \nu \rangle = 75 GeV$, as function of $Q^2$. The dashed and dotted curves are the results of calculations, taking into account only the effect of formation length, or CT. The solid curve incorporates both.