Color transparency: 33 years and still running.

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I review history of the color transparency (CT) which started with discovery of the $J/\psi$ meson, discovery of high energy CT phenomena and the recent progress in the investigations of CT at intermediate energies.

1. Historical introduction

One of the distinctive properties of QCD is the suppression of the interaction of small size color singlet wave packets with hadrons. It plays a key role in ensuring approximate Bjorken scaling in deep inelastic scattering, in proving QCD factorization theorems for high energy hard exclusive processes, etc. It leads to a number of color transparency (CT) phenomena in the hard coherent / quasielastic interactions with nuclei at high energies. Also, the CT phenomenon allows to probe minimal small size components in the hadrons. In addition, at intermediate energies CT phenomena provide unique probes of the space time evolution of wave packets which is relevant for interpretation of the RHIC heavy ion collision data.

For me the story of CT goes back to the discovery of $J/\psi$. It was impossible to explain within the concepts of the pre-QCD theory of strong interactions why the decay width of $J/\psi$ is so small, and (this was learned soon after its discovery) why the photoproduction cross section is so small. These issues were subject of numerous discussions between Leonya Frankfurt and Volodya Gribov during the winter of 74-75 with VG trying to reconcile $J/\psi$ properties with the soft Pomeron logic and LF arguing that for a system consisting of heavy quarks the radius should be significantly smaller than one given by radius of pion emission (this was in contrast to the widely accepted idea at that time due to Fermi, that the radius
of a hadron is determined by the pion cloud and therefore should be approximately universal). More generally LF argued that all matrix elements involving heavy quarks should be suppressed, leading to a strong reduction of the cross section of $J/\psi -$ nucleon interaction ($\propto 1/M_{J/\psi}^2$) and "an unusual conclusion that nucleon becomes transparent to the hadrons built of heavy quarks".\cite{1} This was a clear break with the strong interaction picture with one soft scale which was discussed before $J/\psi$.

A perturbative model for the interaction of hadrons via two gluon exchange was applied to $J/\psi - N$ interaction by Gunion and Soper\cite{2} who demonstrated that within the model the smallness of the $J/\psi$-nucleon interaction is related to the spacial small size of $J/\psi$. Arguments that the suppression should be present also in the nonperturbative domain were given in\cite{3} where it was argued also that small $J/\psi(\psi')$ nucleon cross section extracted from the photoproduction data using the vector dominance model underestimates the genuine $J/\psi - N$ and especially $\psi' - N$ cross section by a large factor.

An independent development was the discussion of the hard exclusive processes like nucleon form factor, large angle hadron-hadron scattering in the large $Q^2$ limit. A debate was going on whether the minimal Fock space components highly localized in space give the dominant contribution in the kinematic range studied experimentally, or the process is dominated by the end point contributions corresponding to quark - gluon configurations of average size. For a recent review see \cite{4}.

A. Mueller has suggested to use exclusive processes off nuclei, namely large angle reaction $pA \rightarrow pp(A - 1)$ in order to discriminate between the two mechanisms,\cite{5} while S.Brodsky\cite{6} made a prediction that the cross of the process $\pi A \rightarrow \pi p(A - 1)$ should be proportional to the number of protons in the target. It is feasible to study these processes as well as quasielastic electron - nucleus scattering only in the kinematics where at least one hadron in the final state has relatively small momentum leading to a need to take into account space time evolution of the quark-gluon wave packets involved in the collision which greatly reduces the CT effect \cite{7}.

This called for finding high energy processes which are dominated by the interaction of hadrons in small size configurations which could be legitimately calculated in pQCD and which are not affected by the space-time evolution of small wave packets. A key observation was that, due to the possibility of treating configurations as frozen during the collision process one can introduce a notion of the cross section of scattering of a small dipole configuration (say $q\bar{q}$) of transverse size $d$ on the nucleon \cite{8,9} which in the
leading log approximation is given by \(^{10}\)

\[
\sigma(d, x) = \frac{\pi^2}{3} \alpha_s(Q_{eff}^2) d^2 \left[ x_N G_N(x, Q_{eff}^2) + 2/3 x_N S_N(x_N, Q_{eff}^2) \right],
\]

where \(Q_{eff}^2 = \lambda/d^2, \lambda = 4 \div 10, \) and \(S\) is the sea quark distribution for quarks making up the dipole. Here, in difference from the original estimate, we include also the contribution of quark exchanges which is important for the interactions at intermediate energies. Note that Eq.(1) predicts a rapid increase of the dipole -hadron cross section with increase of energy which is qualitatively different from the expectation of the two gluon exchange model \(^2\) where cross section does not depend on energy.

First, we will consider the case a more simple case of high energy CT where only two conditions are required: dominance of small size configurations and smallness of \(q\bar{q} - N\) interaction. Next we will consider a more complicated case of CT in the intermediate energy processes where it is masked to large extent by the expansion effects. For a recent extensive review of the CT phenomena see.\(^{11}\)

2. Discovery of high energy CT

To observe CT in a high energy process one needs to find a trigger which selects small size configurations in the projectile. One idea is to select a special final state: diffraction of a pion into two high transverse momentum jets. Qualitatively one expects in this case \(d \sim 1/p_t(jet).\) Another idea is to select a small initial state - diffraction of a longitudinally polarized virtual photon into a meson. It employs the decrease of the transverse separation between \(q\) and \(\bar{q}\) in the wave function of \(\gamma^*_{L,N}, d \propto 1/Q.\) The pQCD results for these processes where first derived in \(^{8,12}\), with the proofs of the QCD factorization for these processes given for dijet production in \(^{10}\) and for meson production in \(^{13}\) (where in addition to production of vector mesons a general case of meson production: \(\gamma^*_{L} + N \rightarrow "meson\ system" + "baryon\ system"\) was considered).

2.1. Pion dissociation into two jets

The space time picture of the process is as follows - long before the target pion fluctuates into \(q\bar{q}\) configuration with transverse separation \(d,\) which elastically scatters off the target with an amplitude which for \(t = 0\) is given by Eq.(1) (up to small corrections due to different off shellness of \(q\bar{q}\) pair in the initial and final states, followed by the transformation of the pair into
two jets. A slightly simplified final answer is

\[ A(\pi N \rightarrow 2 \text{jets} + N)(z, p_t, t = 0) \propto \int d^2 \psi_{q\bar{q}}(d, z) \sigma_{q\bar{q}N}(d, s)e^{ip_t d}, \]

(2)

where \( z \) is the light-cone fraction of the pion momentum carried by a quark, \( \psi_{q\bar{q}}(z, d) \propto z(1 - z)d_{-0} \) is the quark-antiquark Fock component of the meson light cone wave function. Presence of the plane wave factor in the final state leads to an expectation of an earlier onset of scaling than in the case of the vector meson production where vector meson wave function enters.

The FNAL experiment\(^{14}\) confirmed key CT predictions of \(^{8}\): a) a strong increase of the cross section of the \( \pi + A \rightarrow "\text{two jets}" + A \) process with \( A(\text{carbon, and platinum}) \): \( \sigma \propto A^{1.61 \pm 0.08} \) as compared to the prediction \( \sigma \propto A^{1.54} \); b) the \( z^2(1 - z)^2 \) dependence of the cross section on the fraction of energy \( z \) carried by the jet, c) the \( k_t \) dependence of the cross section. Note that the CT prediction for the A-dependence was a factor of seven different from the A-dependence for the soft diffraction.

In the recent update of the analysis Ashery reported\(^{15}\) a fit to the \( z \) distribution using Gegenbauer polynomials for different ranges of \( p_t \). For \( 1.25 \leq p_t \leq 1.5 \text{ GeV/c} \) higher order polynomials appear to be important. Since the CT is observed for this \( p_t \) range as well this indicates that squeezing occurs already before the leading term \((1 - z)z\) dominates.

### 2.2. Vector meson production at HERA

Exclusive vector meson production was extensively studied at HERA. The leading twist picture of the process\(^{12}\) is, in a sense, a mirror image of the dijet production - virtual longitudinally polarized photon first transformed to a small transverse size pair which interacts elastically with a target and next transforms to a vector meson. Hence the process is described by the same equation (2) as for pion case with a substitution of the plane wave \( q\bar{q} \) wave function by the \( q\bar{q} \) wave function of the longitudinally polarized virtual photon.

The extensive studies of the vector meson production were performed at HERA. Several of the theoretical predictions were confirmed including fast \( x \)-dependence of the process at large \( Q^2 \), consistent with the \( x \)-dependence of \( G_N^2(x, Q_{eff}^2) \), and convergence of the \( t \)-dependence to the universal one

\*In QCD a naive expectation of the CT that the amplitude is proportional to \( A \) is modified\(^{8,12}\) due to the leading twist gluon shadowing which should be present at sufficiently small \( x \). This effect is not important for the \( x \) range of the experiment\(^{14}\).
at large $Q_{eff}^2$ where it is given by the two gluon form factor. At the same time the data confirm a conclusion of the model studies\cite{16} that in a wide range of virtualities one needs to take into account a higher twist effect of the finite transverse size of $\gamma_L$ to explain the absolute cross section and $t$-dependence of the data. The leading twist dominance for the absolute cross section for all mesons and for the $t$-dependence for light mesons requires very large $Q^2$ since only in this case one can neglect the transverse size of the $q\bar{q}$ pair in $\gamma_L$ as compared to that in the meson wave function. The same mechanism leads to $Q_{eff}^2/Q^2 \ll 1$ even at large $Q^2$.

To summarize this section. The presence of small size $q\bar{q}$ Fock components in light mesons is unambiguously established. At transverse separations $d \leq 0.3$ fm pQCD reasonably describes small "$q\bar{q}$ - dipole" - nucleon interactions for $10^{-4} < x < 10^{-2}$. Color transparency is established for the small dipole interaction with nuclei for $x \sim 10^{-2}$. Further studies of high energy CT and onset of color opacity will be performed at LHC in the ultraperipheral heavy ion collisions, see\cite{17} for a review.

3. Color transparency for intermediate energies

3.1. Expansion effects

In this section we discuss searches for CT at Jlab and BNL which correspond to the kinematics where the expansion / contraction of the interacting small system is very important (essential longitudinal distances are not large enough for using of the frozen approximation) and strongly suppresses color transparency effect\cite{7,18}.

The maximal longitudinal distance for which coherence effects are still present is determined by the minimal characteristic internal excitation energies of the hadron $h$. The estimates\cite{7,18} show that for the case of a nucleon ejectile coherence is completely lost at the distances $l_c \sim 0.3 \div 0.4$ fm $\cdot$ $p_h$, where $p_h$ is measured in GeV/c\footnote{It is of interest that a much larger value of $l_c/p_h$ is assumed in modeling of heavy ion collisions at RHIC.}.

To describe the effect of the loss of coherence two complementary languages were suggested. In Ref.\cite{7} based on the quark-gluon representation of point-like configuration (PLC) wave function it was argued that the main effect is quantum diffusion of the wave packet so that

$$\sigma^{PLC}(Z) = (\sigma_{hard} + \frac{Z}{l_c} (\sigma - \sigma_{hard} ) ) \theta(l_c - Z) + \sigma \theta (Z - l_c) . \quad (3)$$
This equation is justified for an early stage of time development in the leading logarithmic approximation when perturbative QCD can be applied. Also, one can expect that Eq. (3) smoothly interpolates between the hard and soft regimes. A sudden change of $\sigma_{PLC}$ would be inconsistent with the observation of an early (relatively low $Q^2$) Bjorken scaling\cite{19}. Eq. (3) implicitly incorporates the geometric scaling for the PLC - nucleon interactions which for the discussed energy range includes nonperturbative effects.

The time development of the $PLC$ can also be obtained by its interaction with a nucleus using a baryonic basis for the wave function of PLC:

$$|\Psi_{PLC}(t)\rangle = \sum_{i=1}^{\infty} a_i \exp(iE_it) |\Psi_i\rangle = \exp(iE_1 t) \sum_{i=1}^{\infty} a_i \exp \left( \frac{i(m_i^2 - m_1^2)t}{2P} \right) |\Psi_i\rangle,$$

where $|\Psi_i\rangle$ are the eigenstates of the Hamiltonian with masses $m_i$, and $p$ is the momentum of PLC which satisfies $E_i \gg m_i$. As soon as the relative phases of the different hadronic components become large (of the order of one) the coherence is likely to be lost.

Numerical results of the quantum diffusion model\cite{7,19} and the model based on the expansion over hadronic basis with sufficiently large number of intermediate states\cite{17} give similar numerical results. However though both approaches model certain aspects of dynamics of expansion, a complete treatment of this phenomenon in QCD is so far missing. In particular, the phenomenon of spontaneously broken chiral symmetry may lead to presence of two scales in the rate of expansion, one corresponding to regime where quarks can be treated as massless, and another where virtualities become small enough and quark acquire effective masses of the order of 300 MeV.

### 3.2. Large angle quasielastic $A(p,2p)$ process

First data on the CT reaction $A(p,2p)$ were obtained at BNL. They were followed by the dedicated experiment EVA. The final results of EVA\cite{20} can be summarized as follows. Our calculation within the eikonal approximation with proper normalization of the wave function agrees well the $p_p=5.9$ GeV/c data. The transparency increases significantly for $p_p=9$ GeV/c where $t_c=2.7$ fm. Hence momenta of the incoming proton $\sim 10$ GeV are sufficient to rather significantly suppress expansion effects. Hence one can use proton projectiles with energies above $\sim 10$ GeV to study other aspects of the strong interaction dynamics. At the same time eikonal approximation level transparency for $p_p=11.5 \div 14.2$ GeV/c represents a problem for all current models including those which were specifically suggested to explain
initial indications of the non-monotonous energy dependence of the transparency. This is because the drop of the transparency occurs over a large range of \( s' : 24 \text{ GeV}^2 \leq s' \leq 30 \text{ GeV}^2 \) which is too broad for a resonance\(^{21}\) or for interference of quark exchange and Landshoff mechanisms\(^{22,23}\).

In any case the trend, if confirmed by future data, would strongly suggest that the leading power quark exchange mechanism of elastic scattering dominates only at very large energies. This is consistent with the recent data from Jlab studies of the large angle Compton scattering. These data are not described by the minimal Fock space quark counting rule mechanism, while they agree well with predictions based on dominance of the box diagram contribution \(^{4,24}\).

### 3.3. Color transparency in meson production

It is natural to expect that it is easier to reach CT regime for the interaction/production of mesons than for baryons since only two quarks have to come close together.

The \( J/\psi \) coherent and quasielastic photoproduction experiments did find a weak absorption of \( J/\psi \) indicating presence of CT. There was also evidence for CT in the \( \rho \)-meson production. However these experiments did not have good enough resolution in the missing mass to suppress hadron production in the nucleus vertex, making interpretation of these experiments somewhat ambiguous.

A high resolution experiment of pion production recently reported evidence for the onset of CT\(^{25}\) in the process \( eA \rightarrow e\pi^+A^* \). In the chosen kinematics \( \vec{p}_e || \vec{q} \) which minimizes contribution of the elastic rescattering. The coherent length defined as the distance between the point where \( \gamma^* \) converted to a \( q\bar{q} \) and where \( q\bar{q} \) interacts with a nucleon - \( l_{in} = (Q^2 + M^2_{q\bar{q}}/2q_0) \) is small for the kinematics of \(^{25}\) and varies weakly with \( Q^2 \). This simplifies interpretation of the \( Q^2 \) dependence of the transparency as compared to the case of small \( x \) where \( l_{in} \) becomes comparable to the nucleus size. The experimental results agree well with predictions of\(^{26}\) where CT was calculated based on the quantum diffusion model - Eq. (3).

It is worth emphasizing also, that in the Jlab kinematics one probes large \( x \) processes, which are dominated for the pion case (and probably also for the \( \rho \)-meson case) in the pQCD limit by the contribution of the ERBL region. In this case \( l_{in} \) has a different meaning than for small \( x \) processes where the DGLAP region dominates. It corresponds to the longitudinal distance between the point where \( \gamma^* \) knocks out a \( q\bar{q} \) pair from the nucleon and the nucleon center. This distance can be both positive and negative, and
hence its variation does not lead to a change of the rate of the absorption of the produced pair by the other nucleons.

Results for the $\rho$-meson production where also reported at this workshop.\textsuperscript{27} To interpret this experiment one needs to take into account the effect of absorption due to decays of $\rho^0$ to two pions inside the nucleus, and the elastic rescattering contribution which is more important in this case than in the pion experiment since the data are integrated over a large range of the transverse momenta of the $\rho$ meson.\textsuperscript{28} Up to these effects, we expect similar transparency for this reaction and for $\pi$-meson production.

4. Directions for the future studies at Jlab

There are already approved plans for extending CT studies of the $A(e,e'p)$, $A(e,e'\pi)$ reactions to much higher energies at 12 GeV. This will finally allow to reach kinematics where $l_c$ is larger than the interaction length for a nucleon/pion in the nuclear media.

A complementary strategy is to use processes where multiple rescatterings dominate in light nuclei ($^2H,^3He$) which allows to suppress the expansion effects. An additional advantage of these processes is that one can use for the calculations generalized eikonal approximation, see review in.\textsuperscript{29} In particular, these reactions are well suited to search for a precursor of CT - suppression of the configurations in nucleons with pion cloud in the hard processes like the nucleon form factors at relatively small $Q^2 \geq 1\text{GeV}^2$ - chiral transparency.\textsuperscript{30} The simplest reaction of this kind is production of a slow $\Delta$ isobar in the process $e^2H \rightarrow e+p+\Delta^0$ which should be suppressed in the chiral transparency regime.

Two other examples are (i) large angle $\gamma + N \rightarrow " \text{meson} " + N$ reaction in nuclei where one should first look for a change of $A$-dependence from $\propto A^{1/3}$ to $\propto A^{2/3}$ already in the region where expansion effects are large due to transition from the vector dominance regime to the regime of point-like photon interaction in which photon penetrates to any point in the nucleus, (ii) $A$-dependence of virtual compton scattering, namely at what $Q^2$ transition from vector dominance regime to the CT regime occurs. HERMES data are consistent with our prediction based on CT and closure - but accuracy of the data is moderate.

To summarize, the high energy CT is well established and will be further studied at LHC and EIC. It is likely that Jlab experiments at 12 GeV will observe significant CT effects for the processes with meson production and will provide allow a decisive test of whether nucleon form factors at $Q^2 \sim 15\text{GeV}^2$ are dominated by PLC or mean field configurations. CT will
allow also to establish interplay between soft and hard physics for many other exclusive large momentum transfer processes at Jlab, EIC, LHC as well as at hadronic factories J-PARC, FAIR.

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