Hard scattering to a three cluster final state is suggested as a method to probe configurations in hadrons containing small size color singlet cluster and a residual quark-gluon system of a finite mass. Examples of such processes include $e + N \rightarrow e + p + \Lambda + M_X$, $p + p \rightarrow p + p + \Lambda + M_X$ where $M_X$ could be a pion(kaon) or other state of finite mass which does not increase with momentum transfer ($Q^2$). We argue that different models of the nucleon may lead to very different qualitative predictions for the spectrum of states $M_X$. We find that in the pion model of nonperturbative $q\bar{q}$ sea in a nucleon the cross section of these reactions is comparable to the cross section of the corresponding two-body reaction. Studies of these reactions are feasible using both fixed target detectors (EVA at BNL, HERMES at DESY) and collider detectors with a good acceptance in the forward direction.
1. Introduction

The QCD analyzes of the eighties have demonstrated that cross sections of hard two-body exclusive processes are expressed through the minimal Fock space components of hadrons involved in the reaction (for recent reviews and references see 1,2). The need to establish at what $Q^2$ minimal Fock space components start to dominate in these processes has stimulated searches for the color transparency phenomena.

It is natural to move one step further and ask a question whether collapsing of three valence quarks to a small size color singlet configuration in a nucleon or of valence quark and antiquark in a meson would result in disappearance of other constituents? Such scenario would be natural in quantum electrodynamics for the case of positronium - the photon field disappears in the case when electron and positron are close together (that is the ratio of the amplitude for positronium to be in the Fock state $e^+e^-\gamma$ and in the Fock state $e^+e^-$ decreases with decrease of of the distance between $e^+$ and $e^-$). However in QCD where interactions at large distances are strong it is possible that non minimal Fock components of the hadron contain configurations with small color singlet clusters without an additional smallness as compared to the minimal Fock component. In fact there is no need to restrict the question to the case of clusters build of the valence quarks in a hadron - one can as well consider any small color singlet cluster - for example a $q\bar{q}$ cluster in the nucleon, a three quark cluster with strangeness or charm in the nucleon, etc.

In this talk we will consider the knock out of the clusters induced both by electrons and by hadrons\(^a\).

2. Exclusive production of forward baryons off nucleons

Over the last few years $q\bar{q}$ clusters in the nucleons and mesons were implicitly considered in the context of the study of exclusive DIS processes: $\gamma_L^* + N \rightarrow \text{"meson"} + \text{"baryon"}$ for which the factorization theorem is valid 4,5 which states that in the limit of large $Q^2$ the amplitude of the process at fixed $x$ is factorized into the convolution of a hard interaction block calculable in perturbative QCD, the short-distance $q\bar{q}$ wave function of the meson, and the generalized/skewed parton distribution (GPD) in the nucleon. The HERA data have confirmed a number of the key predictions of 4 including

\(^a\)As far as we know these processes were first discussed in 3 where they were referred to as star dust processes.
shrinkage of the $t$-distribution the light meson production with increase of $Q^2$ to the limiting value which is close to the slope of the $J/\psi$ production cross section. The $Q^2$ dependence of the slope is consistent with predictions of $^6$ (which extended the analysis of $^4$ to account for the geometrical higher twist effects which arise due to the finite transverse size of the virtual photon wave function) indicating that at $Q^2 \geq 4\text{GeV}^2$ small transverse size configurations in $\rho$-meson are selected and that the suppression of the color dipole - nucleon interaction occurs already for transverse distances $\leq 0.4$ fm.

The proof of the factorization for the meson exclusive production $^5$, is essentially based on the observation that the cancellation of the soft gluon interactions is intimately related to the fact that the meson arises from a quark-antiquark pair generated by the hard scattering. Thus the pair starts as a small-size configuration and only substantially later grows to a normal hadronic size, to a meson. Similarly, the factorization theorem should be valid for the production of leading baryons

$$\gamma^* (q) + p \rightarrow B(q + \Delta) + M(p - \Delta),$$

and even leading antibaryons

$$\gamma^* (q) + p \rightarrow \bar{B}(q + \Delta) + B_2(p - \Delta),$$

where $B_2$ is a system with the baryon charge of two. For example in the case of the process (1) the dominant diagram is given by Fig.1:

In QCD to describe the hard exclusive processes one needs to use generalized (skewed) parton distributions. Since the objects one has to introduce for description of $N \rightarrow N$ transitions and non-diagonal transitions like $N \rightarrow \Lambda, \Delta$ are pretty different we suggest to refer to the first type of distributions as as generalized parton distributions (GPD), while in the case of non-diagonal transitions use the term skewed PD.

To describe in QCD process (1), one needs to introduce a new non-perturbative mathematical object $^7$ in addition to the GPDs and SPDs. It can be called a super skewed parton distribution (amplitude). It is defined as a non-diagonal matrix element of the tri-local quark operator between a meson $M$ and a proton:

$$\int \prod_{i=1}^{3} dz_i^- \exp \left[ i \sum_{i=1}^{3} x_i (p \cdot z_i) \right] \cdot$$

$$\langle M(p - \Delta) | \varepsilon a b c \psi_{j_1}^a (z_1) \psi_{j_2}^b (z_2) \psi_{j_3}^c (z_3) | N(p) \rangle \bigg|_{z_i^+ = z_i^- = 0} = \delta(1 - \zeta - x_1 - x_2 - x_3) F_{j_1 j_2 j_3} (x_1, x_2, x_3, \zeta, t),$$

(3)
Figure 1. Production of a fast baryon and recoiling mesonic system.

where \(a, b, c\) are color indices, \(j_i\) are spin-flavor indices, and 
\(F_{j_1 j_2 j_3}(x_1, x_2, x_3, \zeta, t)\) are the new superSPDs. They can be decomposed into invariant spin-flavor structures which depend on the quantum numbers of the meson \(M\). They depend on the variables \(x_i\) (which are contracted with the hard kernel in the amplitude), on the skewedness parameter \(\zeta = 1 - \Delta^+/p^+\) and the momentum transfer squared \(t = \Delta^2\). In some sense, with this definition of \(\zeta\) the limit \(\zeta \to 0\) corresponds to the usual distribution amplitude, \(i.e.\) skewedness \(\to 0\) means (for appropriate quantum numbers of the current) superSDP \(\to \) “nucleon distribution amplitude”.

Though quantitative calculations of processes (1, 2) will take time, some qualitative predictions could be made right away. First we observe that in the Bjorken limit the light cone fraction of the slow meson satisfies condition:

\[
\alpha_h = \frac{p_M - p_{3M}}{p_N} = \frac{E_h - p_{3M}}{E_N - p_{N3}} = \frac{E_M - p_{3M}}{m_N} = 1 - x
\]

(4)

and its transverse momentum \(p_t\) relative to the \(\vec{q}\) direction been fixed. To ensure an early onset of scaling it is natural to consider the process as a function of \(Q^2\) for fixed \(\alpha_h, p_t\). This way we can make a natural link to the picture of removing a cluster from the nucleon leaving the residual system undisturbed. If the color transparency suppresses the final state interaction between the fast moving nucleon and the residual meson state early enough it would be natural to expect an early onset of the factorization of the cross
section to a function which depends on $\alpha_h$, $p_t$ and the cross section of the electron-nucleon elastic scattering:

$$
\frac{d\sigma(e + N \rightarrow e + N + M)}{d\alpha_M d^2p_t/\alpha_M} = f_M(\alpha_M, p_t)(1 - \alpha_M)\sigma(eN \rightarrow eN),
$$

(5)

where $(1 - \alpha_M)$ is the flux factor and $\sigma(eN \rightarrow eN)$ in the cross section of the elastic $eN$ scattering in the appropriate kinematics.

In the case of the pion production the soft pion limit corresponding to $1 - x \sim m_\pi/m_N, p_t \leq m_\pi$ is of special interest because one could use the factorization theorem and the chiral perturbation theory similar to consideration of the process $eN \rightarrow eN\pi$ at large $Q^2$ and small $W^8$. However reaching this kinematics would require extremely high $Q^2$. At the same time reactions with leading nucleon for $x \leq 0.3$ could be studied at sufficiently large $W$ already at Jlab and HERMES.

Reaction (1) provides also a promising avenue to look for exotic meson states including gluonium. Indeed, if one would consider, for example, the MIT bag model, the removal of three quarks from the system could leave the residual system looking like a bag made predominantly of glue. It is natural to expect that such a system would have a large overlapping integral with gluonium states.

An interesting example of a related process where cluster structure can manifest itself is the deep inelastic exclusive diffraction at large enough $t$:

$$
e + p \rightarrow e + \text{leading } \rho + M + B
$$

(6)

where $-t = -(p_{\gamma} - p_\rho)^2 \geq 2GeV^2$, $Q^2 \geq f\text{ew } GeV^2$ and $p_t(M) \approx p_t(\rho)$ and $p_t(M) \gg p_t(B)$. The $t$-dependence of the process $e + p \rightarrow e + \rho + p$ is predominantly determined by the two-gluon nucleon form factor and it can be fitted as $\approx 1/(1 - t/m^2)^4$ with $m^2 \sim 1GeV^2$ at intermediate energies and $m^2 \sim 0.6GeV^2$ at HERA energies. In the case of scattering off a meson a natural guess would be that the $t$-dependence is much slower - perhaps $\approx 1/(1 - t/m^2)^2$ with similar $m^2$. So for large enough $t$ this process may have cross section comparable to the cross section of the $e + p \rightarrow e + \rho + p$ process. Study of this process could provide a test of the interpretation of the smaller gluon radius of the nucleon indicated by our recent analysis.

3. Hadron induced hard semiexclusive processes

A natural extension of the processes discussed for electron scattering is hadron scattering process:

$$
A + B \rightarrow C_{int} + C_{sp} + D,
$$

(7)
where sufficiently large momentum is transferred to \( C_{\text{int}} \) and \( D \) (scattering at finite c.m. scattering angles in the c.m. frame of \( C_{\text{int}} \) and \( D \)), while \( C_{sp} \) similar to the case of the process 1 is produced in the fragmentation region of either \( A \) or \( B \).

Taking for certainty \( D \) in the target fragmentation of \( B \) we can expect that in the color transparency approximation the process will proceed via scattering of a hadron \( A \) in the minimal Fock space configuration off a color singlet cluster in the hadron \( B \) with minimal number of constituents allowed for the process \( A + \text{"cluster":[} \rightarrow C_{\text{int}} + D \). An obvious practical advantage of these processes as compared to the processes 7 is that one can use different beams - pions, kaons, hyperons to probe the clustering structure of different hadrons while the processes 1 in practice are restricted to the case of proton targets.

The two-body large angle hadron scattering processes are known to satisfy to a good approximation dimensional counting rules, for a review see 10. At sufficiently large momentum transfer the small size configurations should give the dominant contribution and hence the rescattering effects should be small. Hence we expect the scaling relations for these processes of the similar kind for a fixed value of \( \alpha_{C_{sp}} \), \( p_{t C_{sp}} \):

\[
\frac{d\sigma(A + B \rightarrow C_{\text{int}} + C_{sp} + D)}{d\alpha_{sp} d^2p_{t sp}/\alpha_{sp}} = \phi(\alpha_{sp}, p_{t sp})R(\theta_{c.m.}) \left( s/s' \right)^n \]

where \( s' = (p_{C_{\text{int}}} + p_{D})^2 \), \( \theta_{c.m.} \) is the c.m. angle in the \( C_{\text{int}} - D \) system, and \( n \) is expressed through the number of constituents involved in the subprocess in the same way as in the two-body large angle scattering:

\[
n = n_q(A) + n_q(\text{cluster}) + n_q(C_{\text{int}}) + n_q(D) - 2.
\]

There is a number of the processes where the hard subprocess resembles the scattering off two hadrons for which the cross section is known, like the process \( p + p \rightarrow p + p + M_{\text{spect}} \), or \( p + p \rightarrow p + \pi + N_{\text{spect}} \) presented in Fig.2.

In this case we can write an interpolation formulae similar to the ones for the electron scattering: For example,

\[
\frac{d\sigma(p + p \rightarrow p + p + \pi^0)}{d\alpha_{\omega} d^2p_t/\alpha_{\omega}} = F(\alpha_{\pi}, p_t) (1 - \alpha_{p,i}) d\sigma_{pp \rightarrow pp}(s', \theta_{c.m.})
\]

with \( s' \approx (1 - \alpha_{\pi})s \). Since the hard cross section decreases strongly with increase of \( s' \) at fixed \( \theta_{c.m.} \) one expects a strong enhancement of production of mesons with relatively high values of \( \alpha_{\pi} \) in these processes. Also, assuming that the distributions of the small color clusters contributing to
Figure 2. (a) Production of two high $p_t$ baryons and recoiling mesonic system, (b) production of a high $p_t$ pion and a nucleon and recoiling baryonic system.

the electron reaction and to the hadron reactions are about the same we can get scaling relations between the cross section of proton and electron induced processes. For example,

$$\frac{d\sigma(p+p \rightarrow p+p+\pi^0)}{d\alpha_{\pi^0}d^2p_t/\alpha_{\pi^0}} \approx \frac{\sigma(p + p \rightarrow p + p)}{\sigma(eN \rightarrow eN)}, \quad (11)$$

We have performed first estimates of the rate of the production of pions using the discussed mechanism and using a simple model for the $\Gamma_{NN\pi}$ vertex. Enhancement of the scattering off three quark clusters which carry $(1 - x)_{\pi}$ fraction of the total light cone momentum of the nucleon as compared to the scattering off the nucleon as a whole by a factor $(1 - x)_{\pi}^{-10}$ leads to enhanced role of the pion cloud and results in the cross sections of the same magnitude as the elastic $pp$ scattering. We are currently performing more detailed studies to determine the contribution of this mechanism to the cross section measured by EVA $^{12}$.

We also found that at the intermediate energies $E \leq 10$ GeV studied at EVA $^{12}$ an important background to the discussed mechanism is provided by production of excited nucleon states. Indeed, the cross section of the processes like $pp \rightarrow N^* + p$ at $\theta_{c.m.} \sim 90^0$ is comparable to the elastic $pp$ scattering. Moreover if we would sum over a sufficient range of masses of $N^*$’s we should expect to find a cross section which is enhanced as compared to the elastic scattering since it does not contain a smallness for three quarks to transform to a particular state (nucleon). If we use the quark counting rules as a guide, the ratio of quasielastic and elastic processes should increase with $s$ as $\propto s^2$. At sufficiently high energies kinematics of the meson production in these processes is qualitatively different from the process 7 since the average pion transverse momenta in this case increase.
with $s$ approximately as $\propto \sqrt{s}$ (for the case of the $N\pi$ final state). However we have checked that for $E_{inc} \leq 10\text{GeV}$ it is difficult to separate fragmentation in the initial and final states even in the simplest reaction $pp \to ppm^0$ except for production of pions at very small $p_t$.

In the previous discussion we assumed that hard two body subprocess is dominated by the scattering of constituents in small size configurations, so that the interaction with residual system could be neglected. However the current data on transparency in high-energy large angle $(p,2p)$ reactions suggests a rather complicated interplay of the contributions of large and small size configurations. In this case the initial and final state interactions with the would be spectator would be possible. For example in the process $pp \to ppm^0$ with $\pi^0$ a spectator both the proton in the initial state and both protons in the final state can rescatter off the pion. Presence of multiple rescatterings will lead to rather complicated patterns of angular correlations similar to those found for the large angle $p^2H \to ppn$ process in $^{11}$. These rescatterings will weakly affect distribution over $\alpha_M$ though they would change overall absolute value of the cross section and lead to broadening of the $p_t$ distribution of the spectator.

Another possible source of angular asymmetries is postselection of the initial state which could be different at intermediate energies when the size of three quark cluster is not too small. The requirement of the elastic scattering off the three quark cluster may select the alignment of the cluster relative to the reaction axis hence modifying the angular distribution of the spectator system. In particular this effect can emerge as a kind of a hadron level Sudakov radiation, see discussion in $^{12}$.

To summarize, a systematic study of the lepton and hadron induced hard semiexclusive reactions with leading baryons is necessary. It would provide a qualitatively new information about correlations of partons in hadrons and as well as about the dynamics of the large angle elastic scattering.

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