Probing the exchanged object(s) in diffractive scattering

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Abstract

The reaction mechanisms of the following proton diffractive scattering processes are studied and compared with one another: $\gamma^*p \rightarrow Vp, \gamma^*p \rightarrow Xp, pp \rightarrow (\Lambda K^+)p$ and $pA \rightarrow \Lambda K^+A$ (Here, $\gamma^*$ stands for the space-like photon in inelastic electron-proton scattering, $V$ for the vector mesons $\rho, \omega, \phi, J/\psi$, and $A$ for a target nucleus.) It is shown that, by taking parity, and C-parity conservation into account, the existing data for these reactions strongly suggest the following: A considerable part of the objects exchanged between projectile and target in the above-mentioned processes are virtual quark-antiquark pairs in color-singlet states with $J^{PC} = 0^{--}$, $I^G = 0^+$, where $J$ stands for total angular momentum, $I$ for isospin, $P$, $C$ and $G$ stand for parity, C-parity and G-parity respectively. Such quark-antiquark pairs are created by soft-gluon interactions. New experiments are suggested; and predictions for such experiments are made.
Diffractive processes in lepton-nucleon scattering at relatively large invariant lepton-momentum transfer \((Q^2)\) have received much attention recently [1-5]. Considerable efforts have been devoted to the problem whether, and if yes how, nucleon diffractive scattering in such lepton-induced processes is related to that in hadron-induced reactions. The questions in this problem-complex are usually discussed in the Regge-language: What are the similarities and/or the differences between “the hard pomeron” and “the soft pomeron”? How does (do) the pomeron(s) interact with the photon in photo-production and electroproduction processes? What are the properties of “the pomeron structure function(s)” ? etc.. While the answers to these questions are still under debate [1-5], we think it may be useful also to discuss them in a different language — namely directly in terms of gluons and quarks in accordance with QCD. To be more precise, stimulated by the ideas which have been discussed already for a long time namely: “pomeron-exchange dominates diffractive reactions” [1-5] “pomeron can be interpreted as a system of gluons” [6], we propose to study the mechanism(s) of exchange of gluon-systems in such processes directly.

We consider inelastic lepton-nucleon scattering in the small \(x_B\) \((<10^{-2}, \text{say})\) region at a given \(Q^2\). It is in this kinematical region that large rapidity-gap events have been observed [1-5] indicating the existence of diffraction. It is also in this region that structure function measurements together with empirical analyses [7] show the following: the gluon-density for small \(x_B\) is much higher than that e.g. at \(x_B \sim 0.1\) for the same \(Q^2\). Hence, if such diffractive scattering processes are indeed due to “exchange of systems of gluons”, these gluons are expected to be very “soft”, in the sense that even in a fast moving frame (e.g. the photon-proton c.m.s. frame) they do not carry much longitudinal momenta. Due to lack of sufficient energy and momentum, the chance for such a “soft” gluon to fluctuate and create for a limited time-interval a quark-antiquark-pair is very small. But, due to the possibility of gluon-gluon interactions allowed by QCD in general, and the processes of virtual quark-antiquark production by two or more gluons (as illustrated in Fig.1) in particular, we are led to consider, in diffractive processes, the interaction between the virtual photon \(\gamma^*\) and such virtual quark-antiquark \((q\bar{q})\) pairs. Because of the large rapidity gap, the \(q\bar{q}\)-pairs are
expected to be color singlets. What else do we know about such $q\bar{q}$-states? What quantum numbers can such states have?

In order to answer these two questions, it is useful to recall the similarities and the differences of QCD and QED, in particular the dynamical constraints for $\gamma$-decay of positronium and their time-reversed processes, namely fermion-pair production through photon-photon interactions. In analogy to QED [8], we see that parity-conservation and C-parity-conservation play important roles in describing the decay and the formation of $q\bar{q}$ pairs in collision processes of soft-gluons. To be more precise, in analogy to positronium, a two-gluon state has C-parity +1, and therefore the only $q\bar{q}$ states that can decay into two gluons must have $L+S$ even, where $L$ and $S$ stand for relative angular momentum and total spin of the $q$ and the $\bar{q}$. This implies that the lowest $C = +1$ state which can decay into two gluons is the ground-state — the singlet state characterized by $J = L + S = 0$, parity $-$, and C-parity $+$. This also implies: When two soft gluons meet each other and form, for a finite time-interval, a color-singlet state, this state is associated with the quantum numbers $J^{PC} = 0^{-+}$, where $J$ stands for the total angular momentum, P the parity and C the C-parity of the $q\bar{q}$ system. We also note that the quark $q$ may be $u, d, s, c, ...$ and that isospin conservation and G-parity conservation dictate: The isospin ($I$) and the G-parity ($G$) of such $q\bar{q}$ systems should be $I^{G} = 0^{+}$. It is expected that the $q\bar{q}$-pairs formed by two-gluon interactions (see Fig. 1) play a dominating role, and this expectation is based on the following simple considerations: The interaction between soft-gluons is very complicated. Such gluons are expected to interact with one another according to QCD. But, because of the magnitude of the running coupling constant, description of their interaction by using perturbative methods are no more reliable. All we can say in this connection is that, statistically, the chance for two soft-gluons to interact with each other and form such a state is expected to be larger than that for three or more gluons to come together. Besides, since direct gluon-gluon interactions are allowed in QCD, $q\bar{q}$-creation is also possible when, for example, two gluons first directly interact with each other to become one gluon, and then produce the $q\bar{q}$-pair with a third gluon.

In order to answer the question: “What do we expect to see experimentally, when such
\(\gamma^*(q\bar{q})\) interactions take place?”, we note that \(q\) and \(\bar{q}\) of the above-mentioned \(q\bar{q}\)-system carry (opposite) electric charges. Hence, for the incoming photon \(\gamma^*\) which has a transverse dimension of order \(Q^{-2}\), \(q\) and \(\bar{q}\) may act — depending on its transverse dimensions — either (A) as one single object — perhaps as an electrical dipole with extremely small dimensions (compared with the transverse dimension of \(\gamma^*\) mentioned above), or (B) as a neutral system which consists of two opposite electric charges. We now discuss these two cases separately.

(A) What do we expect to see in those cases in which \(Q^2\) of the virtual photon is small, such that its transverse dimension is large enough for the \(q\bar{q}\)-system to act as one object and the transfer of momentum is not so large to “break up” this system? In order to answer this question, we recall that the photon and the gluon have very much the same properties as far as spin, parity and C-parity are concerned. In fact, taken together with the well-established conservation laws in electrodynamic and hadronic reactions \([8]\), a space-like \(q\bar{q}\)-pair (with \(J^{PC} = 0^{-+}\)) may absorb a virtual photon and become a time-like \((\gamma^* q\bar{q})\)-system with \(J^{PC} = 1^{--}\) and \(I^G = 0^- \) or \(1^+\) (due to electromagnetic interaction which conserves neither \(I\) nor \(G\)). That is to say, the final state of such a \(\gamma^*-q\bar{q}\) reaction may be a vector-meson, provided that the \(J^{PC} = 0^{-+} q\bar{q}\)-system interacts with the exchanged virtual photon \(\gamma^*\) as an entire object! This means, we should see vector-mesons in such lepton-nucleon processes in the small \(x_B\) region, in particular:

\[e^- + p \rightarrow e^- + V + p\]

where \(V\) stands for \(\rho^0, \omega, \phi, J/\psi\).

Furthermore, we should see that the cross section for such processes is proportional to the number density of such \(q\bar{q}\)-pairs associated with the proton. It implies in particular that, at a given \(Q^2\), the production rate of vector mesons are expected to increase with increasing \(W^2\) (where \(W\) is the total c.m. energy of the photon-proton system) — independent of the quantum numbers of the vector mesons. This is because, at fixed \(Q^2\),

\[W^2 = Q^2(1/x_B - 1) + M^2\]
(where M stands for the proton-mass) increases with decreasing $x_B$. But, since for smaller $x_B$ values, the gluon-density is higher [7], and thus the chance to produce such $J^{PC} = 0^{-+}$ $q\bar{q}$-pairs is higher. This implies, the rate of production of such $(\gamma^* q\bar{q})$-systems (the vector mesons), in particular the total cross-section $\sigma_T + \sigma_L$ for vector meson production is expected to become larger for increasing $W^2$. To compare this with the data quantitatively, we take the number-density of the colorless object (which consists of $q\bar{q}$) from the data for the diffractive structure function $F^{D(3)}(\beta; x_B, Q^2)$ [1] and integrate over $\beta$, (Here, $\beta$ stands for the fraction of the longitudinal momentum of the colorless object carried by the struck charged constituent). The obtained result shows that the number density of such colorless objects increases with decreasing $x_B$. The comparison between the data [2] and the calculated result is shown in Fig.2. As expected, the agreement is reasonable. It should be mentioned in this connection that, since (according to the proposed picture) the $q\bar{q}$ system in the color-singlet $J^{PC} = 0^{-+}$ state is due to the interaction between two soft-gluons which exist only in the small $x_B$ region, the $W$-dependence of the production rate of vector-mesons is expected to apply only for sufficiently small $x_B(<10^{-2}$, say) values. This means, the vector meson production at large $x_B$-values, for example those of NMC [3], are not “the knocked-out color-singlet ($\gamma^* q\bar{q}$) systems” (which due to the interaction with $\gamma^*$ has $J^{PC} = 1^{--}$).

Furthermore, for increasing $Q^2$, the production rate should decrease. This is because the $q\bar{q}$-system is expected to break-up more easily when the transverse dimension $Q^{-2}$ of $\gamma^*$ becomes smaller, so that the geometrically more point-like $\gamma^*$ can hit only either $q$ or $\bar{q}$. This, taken together with the fact that the transfer of momentum increases for increasing $Q^2$, show that we should see the following: The $q\bar{q}$-system breaks-up much easier when $Q^2$ becomes large! As we can explicitly see in Fig.2 (note the $Q^2$-dependence of the cross-section for vector-meson production shown on the left-hand-side in the figure) and the corresponding multi-hadron production processes discussed in (B) below, also these characteristic features have indeed been observed [2,3].

(B) Let us now examine in more detail the case in which $Q^2$ is so large, that (because of the reason mentioned above) it is more probable for $\gamma^*$ to hit only one of the charged
objects $q$ or $\bar{q}$. The struck object ($q$ or $\bar{q}$) can absorb $\gamma^*$ and “fly away” from the rest of the system (mainly $\bar{q}$ or $q$). Due to color-forces, the “leading $q$ and $\bar{q}$” is expected to behave like the $q\bar{q}$-pair similar to that in high-energy electron-positron scattering (see e.g. Ref.9) where a color-string is generated which breaks up into hadrons [10]. In order to see why these two kinds of processes are expected to be so similar to each other, we note once again that, since a $(q\bar{q})$-pair due to $gg$ is in the $J^{PC} = 0^{--}$ state, the $(\gamma^*-q\bar{q})$-system (i.e. the system $q\bar{q}$ after one of its charged member has absorbed the $\gamma^*$) is in the $J^{PC} = 1^{--}$ state. It means, the latter has the same quantum numbers of the (initial, intermediate and final) state of the $e^-e^+ \rightarrow \gamma^* \rightarrow q\bar{q}$ process. Having these arguments in mind, we reach the conclusion that, in such cases, we should see the following: The produced hadrons are distributed along the scattering axis symmetric with respect to the center of mass of the $\gamma^*-(q\bar{q})$ system. Only the hadrons on the end of the color-string can have large momenta (both the longitudinal component $p_{||}^*$ and the transversal components $p^*_\perp$ with respect to the collision axis). In other words, if we follow H1-Coll. [1] and define $x_F = 2p_{||}/M_X$ where $M_X$ is the invariant mass of the system of produced hadrons, we should see that most of the hadrons are concentrated near $x_F = 0$ and have very small $p^2_\perp$. In order to compare the proposed picture with the data [1] in a quantitative manner, we use the Lund model as implemented in JETSET [10] to calculate the $x_F$-distribution, the $\langle p^2_\perp \rangle$ vs. $x_F$ plot and the energy flow as a function of pseudo-rapidity in the center of mass system of the photon and the exchanged object. The obtained results are shown in Fig. 3a and 3b. and Fig.4. It should be mentioned that, while the data in Figs. 3(a) and 3(b) are given [1] at fixed $M_X$ ($M_X = 10$ GeV), those in Fig.4 are given [1] for three different ranges of $M_X$. Hence, taken together with the the kinematical relationship $M_X^2 \approx Q^2(x_P/x_B - 1)$ which shows that $Q^2$ and $M_X^2$ are directly proportional to each other for fixed values of $x_P$ and $x_B$, we can at least use Fig.4 to check the $Q^2$-dependence of the proposed picture for fixed $x_B$ and $x_P$. Having in mind that the transverse dimension of $\gamma^*$ becomes smaller and the transfer of momentum to the struck quark or the antiquark increases with increasing $Q^2$ and thus with increasing $M_X^2$, we expect to see that the multi-hadron events should be more jet-like for increasing
As we can see in Fig.4, this expectation is indeed in agreement with the data [1]. It would be interesting to see whether this trend will continue for even larger $M_X$-values in future experiments.

We next turn our attention to diffractive hadron-hadron collisions, and ask: Do we also see experimental indications for the exchange of spin-zero virtual $q\bar{q}$-systems due to interactions between soft-gluons in such collision processes? One way of probing the spin of the exchanged $q\bar{q}$-pair in diffractive scattering is to look at proton diffractive dissociation processes in which the final states are simple. In this sense, the reactions $pp \rightarrow (\Lambda K^+)p$ and $pA \rightarrow (\Lambda K^+)A$ are ideal.

Such experiments have already been performed [11,12]. Very striking polarization effects have been observed in the former [11] and similar measurements are underway in the latter [12]: The produced $\Lambda$ observed in [11] is polarized (with respect to the axis $\vec{p}_B \times \vec{p}_\Lambda$ where $\vec{p}_B$ and $\vec{p}_\Lambda$ are the 3-momenta of the proton beam and the outgoing $\Lambda$ respectively) although neither the projectile nor the target is polarized. The polarization of the $\Lambda$ is very large ($62\% \pm 4\%$) – much larger than those observed in inclusive reactions $pp \rightarrow \Lambda X$ [13]. This piece of experimental fact, together with strangeness conservation in hadronic processes, makes the study of this process even more interesting.

We recall that the striking features especially the flavor-dependence, the projectile-dependence of asymmetries in single-spin hadron-hadron collisions can be described in terms of a relativistic quark-model\[13\] in which valence quarks are treated as Dirac particles confined in a spatially extended hadron. It is shown that such valence quarks perform orbital motion, the spin states of the valence quarks with respect to the polarization axis of a polarized hadron are determined by the wave function of the hadron, and thus a meson directly formed by a valence quark near the front surface of the polarized hadron (with respect to the target hadron which provides a suitable antiseaquark) acquires an extra amount of transverse momentum due to the orbital motion of the valence quark. \textit{This implies the existence of a close relationship between the polarization of the valence quarks of the transversely polarized projectile hadron and the transverse motion of the directly formed mesons in the projectile}
fragmentation region. In other words, in this picture, knowing the probability of observing a meson on one side (left or right) of the collision axis, the chance for the valence quarks of the projectile to be polarized in a given direction perpendicular to scattering plane is determined. Having this picture in mind, we see that the $J^{PC}$ of the $s\bar{s}$-pair plays a decisive role: As graphically demonstrated in Fig.5, the $\Lambda$ in $pp \to (\Lambda K^+)p$ is expected to be negatively polarized with respect to the production plane. To be more precise, the produced $K^+$ in this kinematical region is the fusion product of a $u$-valence quark and a strange antiquark $\bar{s}$ form the sea. Because of the correlation between the polarization and the transverse momentum of the valence quarks, as explained above (and in more detail in Ref.14), the valence quark $u_v$ has a larger probability to be polarized downwards (than upwards). Since $K^+$ is a spin-0-particle, the $\bar{s}$ quark originating from the above-mentioned $J^{PC} = 0^{-+}$ system is polarized upwards. The $\Lambda$ which goes left (because of momentum conservation) is directly formed by the remaining $ud$-diquark of the projectile proton and the downwards polarized $s$-quark $s_s$. Since the $ud$-diquark is a spin-0-system, the polarization of $\Lambda$ is determined by the polarization of $s$-quark. It is opposite to $\vec{n} \equiv \vec{p}_B \times \vec{p}_\Lambda/|\vec{p}_B \times \vec{p}_\Lambda|$ and hence negative. Needless to say that, the conclusion we reached does not depend on the fact that we have chosen to consider the $K^+$’s moving to the right with respect to the collision axis (as shown in this figure). By considering those moving to the left, by replacing “downwards” by “upwards” and vice versa in the discussions correspondingly, and by keeping the definition of $P(\Lambda)$ in mind, we obtain the same result. Here, we see among other things that, in the framework of the relativistic quark model [14], $P_\Lambda$ for the diffractive process $pp \to (\Lambda K^+)p$ could never be larger than that for the inclusive $pp \to \Lambda X$, if the $s\bar{s}$-pair were not spin-zero objects!

Two further remarks should be made in this connection:

First, in a recent paper [15], J. Felix et al published their data on $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ in which the following characteristic features have been observed. (a) $P_\Lambda$ is significantly smaller ($\sim 15\%$) than that observed in [11] (b) The polarization of $\Lambda$ is independent of the fact whether $K^+$ is detected in the same or in the opposite hemisphere as $\Lambda$. Both (a) and (b) are consistent with the proposed picture. This is because, in contrast to the
pp \to K^+\Lambda p$ experiment \cite{11} which is performed at $p_{\text{inc}} \approx 2000$ GeV/c, the experiment $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ is done at $p_{\text{inc}} \approx 27.5$ GeV/c. Here, we note in particular that, although the total center-of-mass-energy is so low, the number of particles in the final state of this reaction is rather high. Hence the chance for this process to undergo a single diffractive process is relatively small. Having in mind that the exchange of a $gg$-system with the above mentioned quantum numbers dominates only in single particle diffractive processes it is expected that the $\Lambda$-polarization in this process \cite{15} should be significantly smaller than that observed in \cite{11}.

In connection with the experimental fact mentioned in (b) we discuss the contributions from single particle diffractive processes to $pp \to p\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ and show that the $\Lambda$ polarization is expected to be independent of the rapidity-distribution of $K^+$ even if the observed final state hadrons are contributions form single diffractive processes. To be more precise, in Fig.6 we show the final states due to the exchange a $J^{PC} = 0^{-+}, I^G = 0^+$ $gg$-state including a number of light quarks and antiquarks $u\bar{u}$ or $d\bar{d}$. Obviously, in such cases, different possibilities of combining the $u\bar{u}, d\bar{d}$ and $s\bar{s}$ pairs to form the observed final states have to be taken into account. Here, the dark sites in these figures stand for “black boxes”. We do not know, and do not care of the details about the reaction mechanisms inside such black boxes, because they do not play a role in the proposed picture. In fact, it is only important that the black box describes a spin-zero state. As illustrative examples, we show in Fig.6 two different possibilities to produce the final state hadrons $\Lambda K^+\pi^+\pi^-\pi^+\pi^-$ in $p-p$-collision by the exchange of a colorless spin-zero $gg$-system. In (i) both $\Lambda$ and $K^+$ are produced by valence-quarks of the projectile. The probability is large that both of them appear in the fragmentation region of the projectile i.e. in the same hemisphere. Here $K^+$ compensates both the transverse momentum and the spin of the produced $\Lambda$ and give raise to the $\Lambda$-polarization. In (ii) one of the produced pions and the $\Lambda$ are produced by the valence quarks of projectile. Since, here, the kaon is produced by sea-quarks there is no kinematical constraints which could force it to be in the same hemisphere as the $\Lambda$. In fact since one of the pions takes over the role played by $K^+$ in case (i) in compensating the transverse
momentum and the spin of the $\Lambda$, the $K^+$ in this case is free — in the sense that it can be either in the same or in the opposite hemisphere relative to $\Lambda$! This means, as far as the $\Lambda$-polarization is concerned the spatial correlation between $\Lambda$ and $K^+$ (in particular whether they are in the same or opposite hemisphere) does not play a role when other spin-zero particles are produced. As we see in Ref. [15], this is in accordance with the experimental findings.

Second, further experimental studies of polarization effects in diffractive dissociation processes, for example in $p(\uparrow)p \rightarrow K^+\Lambda(\uparrow)p$ in which the “beam-$\Lambda$-parameter” $D_{NN}$ is measured, will be helpful especially in probing the spin of the exchanged $s\bar{s}$-pair in diffractive scattering processes. If all exchanged colorless objects have spin zero, we expect $D_{NN} = 1$. Hence the observed $D_{NN}$ in such diffractive processes is — in the proposed picture — a direct measure of the fraction of spin-zero components in the set of all exchanged colorless objects.

Last but not least, the following should also be mentioned. While the $\Lambda$-particles in the fragmentation regions in proton-proton collisions — especially in proton diffractive dissociation processes — are predominantly created through quark-diquark fusion, the production mechanisms of $\Lambda$ in diffractive deep-inelastic electron-proton scattering is very much different: In the latter case, the (large $Q^2$) virtual photon $\gamma^*$ hits either $s$ or $\bar{s}$ of the above-mentioned color-singlet spin-zero $s\bar{s}$-system (formed by collisions of the two soft gluons) and produce a color-string led by $s$ and $\bar{s}$. Because of helicity-conservation in high-energy photon-quark scattering the helicity of the struck $s$ (or $\bar{s}$) has to flip. It implies, after the $\gamma^*-(s\bar{s})$ interaction, the $s$ and $\bar{s}$ should have different helicities in the center-of-mass frame of the $\gamma^*-(s\bar{s})$ system. Having in mind, that the leading $s$ and $\bar{s}$ can give rise to $\Lambda$ and $\bar{\Lambda}$ respectively, and that the polarization of $\Lambda$ ($\bar{\Lambda}$) is completely determined by that of the $s$ ($\bar{s}$), the $\Lambda$ and $\bar{\Lambda}$ are expected to have opposite helicities. This means, by measuring the helicities of the $\Lambda$ and $\bar{\Lambda}$ appearing in opposite hemispheres on an event by event basis, we can experimentally test whether the struck $s\bar{s}$-system is a spin-zero state.

In order to estimate the probability for the $\Lambda-\bar{\Lambda}$ to have opposite helicities quantitatively,
we use the method introduced by Gustafson and H"akkinen [16]. As we know, by using the above-mentioned method, these authors have successfully predicted [16] the longitudinal polarization measured in the recent ALEPH-experiment [17]. Following this method, we consider all possible processes which can contribute to the production of a $\Lambda$-$\bar{\Lambda}$ pair. They are the following:

(a) Both the $\Lambda$ and $\bar{\Lambda}$ are directly formed by the initial $s$ and $\bar{s}$ quarks respectively. The $\Lambda$ ($\bar{\Lambda}$) has the helicity of the original $s$($\bar{s}$)-quark. In this case the above-mentioned helicity correlation is maximal. The $\Lambda$ and the $\bar{\Lambda}$ have opposite helicities provided that the $s$-$\bar{s}$ pair is a spin-zero object.

(b) The $\Lambda$ ($\bar{\Lambda}$) is produced during the fragmentation processes of $s$ and $\bar{s}$ in which the $\Lambda$ ($\bar{\Lambda}$) does not contain the initial $s$ ($\bar{s}$) quark. It is obvious that, in such processes, the helicities of the $\Lambda$ and $\bar{\Lambda}$ are not correlated.

(c) Since such colorless clusters can also be $u$-$\bar{u}$ or $d$-$\bar{d}$ systems so that the produced lambda hyperons can also be the fragmentation products of such light quarks. Having in mind the polarization of $\Lambda$ ($\bar{\Lambda}$) is completely determined by that of the $s$ ($\bar{s}$) quarks, it is clear that these events do not contribute to the $\Lambda$-$\bar{\Lambda}$ helicity correlations.

(d) Produced $\Lambda$-($\bar{\Lambda}$) hyperons which contain initial $s$ ($\bar{s}$) quarks but are decay-products of heavier hyperon resonances. The helicities of these hyperon anti-hyperon pairs are in general also correlated if they originate from initial spin-zero $s$-$\bar{s}$ pairs. They decay into $\Lambda$ - $\bar{\Lambda}$ pairs which will “remember” part of the helicity correlation of the initial $s$-$\bar{s}$.

In order to treat the contribution of those events associated with resonance-decay quantitatively, we calculate the probabilities for the initial helicity correlation of the $s$-$\bar{s}$ pair to be transferred through the intermediate resonances to the final $\Lambda$- $\bar{\Lambda}$ pair. Let us first discuss the production of $\Sigma^0$ which decays electromagnetically into $\Lambda + \gamma$. Here, we recall that according to the method used in Ref.[16] when dealing with such heavy strange particles the non-relativistic quark model can be used to calculate the above-mentioned probabilities. In fact, it is easy to see that the probabilities for the produced $\Sigma$ to have the same or opposite helicity as the original $s$-quark are $P(\Sigma^0, s, +) = 1/3$ and $P(\Sigma^0, s, -) = 2/3$ respectively.
For the decay-process $\Sigma^0 \to \Lambda + \gamma$ the probabilities that the $\Lambda$ should have the same or opposite helicity as the $\Sigma^0$ are $P(\Lambda, \Sigma^0, +) = 1/3$ and $P(\Lambda, \Sigma^0, -) = 2/3$ respectively. This means the probabilities for the $\Lambda$ originating from the original $s$-quark through $\Sigma^0$ decay to have the same or opposite helicity as the $s$-quark are given by:

$$P(\Lambda, \Sigma^0, +) = 1/3$$

$$P(\Lambda, \Sigma^0, -) = 2/3$$

respectively. The corresponding probabilities for $\bar{\Lambda}$ originating from the $\bar{\Sigma}^0$ decay are the same. The probabilities for that the $\Lambda$-$\bar{\Lambda}$ pairs which come from $\Sigma^0$-$\bar{\Sigma}^0$ decays to have the opposite or the same helicities if the $s$-$\bar{s}$ have opposite helicities are given by:

$$P(h_\Lambda = -h_{\bar{\Lambda}}) = P(\Lambda, \Sigma^0, +)P(\bar{\Lambda}, \bar{\Sigma}^0, \bar{s}, +)$$

$$+ P(\Lambda, \Sigma^0, +)P(\bar{\Lambda}, \bar{\Sigma}^0, \bar{s}, -) = 41/81$$

$$P(h_\Lambda = h_{\bar{\Lambda}}) = P(\Lambda, \Sigma^0, +)P(\bar{\Lambda}, \bar{\Sigma}^0, \bar{s}, -)$$

$$+ P(\Lambda, \Sigma^0, +)P(\bar{\Lambda}, \bar{\Sigma}^0, \bar{s}, +) = 40/81$$

Next we note that, according to the analyses carried out by Gustafson and Hämäkinen[16], the hyperon decays $\Sigma^0 \to \Lambda \gamma$, $\Sigma(1385) \to \Lambda \pi$, $\Xi \to \Lambda \pi$ and $\Xi(1530) \to \Xi \pi \to \Lambda \pi \pi$ should be included because their contributions are relatively large and other possible decays should be neglected because their contributions are very small [16]. In Table 1. we list the corresponding probabilities for the other decays. For the anti-hyperons we get the same numerical results. In order to calculate the relative probabilities for observing $\Lambda$ and $\bar{\Lambda}$ which originate from (a), (b), (c) and (d) we again use the Lund-model as implemented in JETSET for the fragmentation of the $s-\bar{s}$-system. Precisely speaking, we calculate the probability for $\Lambda$ and $\bar{\Lambda}$ to have opposite helicities as a function of $(x_F)_{cut}$ which is the minimum of the $x_F$ of $\Lambda$ and that of $\bar{\Lambda}$. The obtained result is shown in Fig.7. Here, we
see that for large \((x_F)_{cut}\) the probability for the \(\Lambda\) and the \(\bar{\Lambda}\) to have different helicities is large. In the small \((x_F)_{cut}\)-region in which the production processes (b) and (c) dominate, there is practically no correlation between the helicities of the hyperons. In other words, the probability turns out to be \(p(h_\Lambda = -h_\bar{\Lambda}) \approx 0.5\), as it should be. Note that, no correlation between the helicity \(h_\Lambda\) of \(\Lambda\) and the helicity \(h_\bar{\Lambda}\) of \(\bar{\Lambda}\) means nothing else but that \(h_\Lambda = h_\bar{\Lambda}\) and \(h_\Lambda = -h_\bar{\Lambda}\) are equally probable. In other words, the probability \(p(h_\Lambda = -h_\bar{\Lambda})\) for \(\Lambda\) and \(\bar{\Lambda}\) to have opposite helicities should be 50%.

In conclusion, the present paper points out that there exist a large number of theoretical arguments and experimental evidences which show the following: A considerable part of the “exchanged colorless object(s) in the diffractive scattering processes, in particular in \(\gamma^* p \rightarrow V p, \gamma^* p \rightarrow X p, pp \rightarrow (\Lambda K^+)p\) and \(pA \rightarrow (\Lambda K^+)A\), where \(\gamma^*\) stand for virtual photon, \(p\) for proton, and \(V\) for vector meson, have the following quantum numbers: \(J^{PC} = 0^-\), \(I^G = 0^+\) where \(J\) stand for for the total angular momentum, \(I\) for isospin, \(P\), \(C\) and \(G\) stand for parity, C-parity and G-parity respectively. Such color-singlet objects which exist for a finite time-interval are formed by soft gluons the density of which are expected to be very high in the small \(x_B\) region of lepton-nucleon scattering processes.

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Table 1. The probabilities for $\Lambda$ originating from different hyperon decays to have the same(+) [opposite(-)] polarization as the initial s-quark. See text for more details.

| Decay                  | $P(H, s, +)$ | $P(H, s, -)$ | $P(\Lambda, H, +)$ | $P(\Lambda, H, -)$ | $P(\Lambda^H, s, +)$ | $P(\Lambda^H, s, +)$ |
|------------------------|--------------|--------------|---------------------|---------------------|-----------------------|-----------------------|
| $\Sigma^0 \rightarrow \gamma \Lambda$ | 1/3          | 2/3          | 1/3                 | 2/3                 | 5/9                   | 4/9                   |
| $\Sigma(1385) \rightarrow \Lambda \pi$  | 5/9          | 4/9          | 1                   | 0                   | 5/9                   | 4/9                   |
| $\Xi \rightarrow \Lambda \pi$            | 5/6          | 1/6          | 9/10                | 1/10                | 23/30                 | 7/30                  |
| $\Xi(1530) \rightarrow \Xi \pi \rightarrow \Lambda \pi \pi$ | 5/9          | 4/9          | 9/10                | 1/10                | 49/90                 | 41/90                 |

TABLES
FIGURES

Fig. 1. Fermion-pair (f ¯f) production in gluon-gluon (gg)-scattering.

Fig. 2. Comparison between data [2,3] and the calculated results (see text) for vector meson production.

Fig. 3. (a) The $x_F$-distribution and (b) the $\langle p_T^2 \rangle$ vs $x_F$ plot for the hadrons produced in $\gamma^*-q\bar{q}$ collisions in the c.m.s. of $\gamma^*-q\bar{q}$, for invariant mass $M_X=10$ GeV. The data are taken from Ref.[1]; they are given at fixed $M_X = 10$ GeV (in the kinematical range $2.5<Q^2<65$ GeV$^2$, $0.01<\beta<0.9$, $0.0001<x_P<0.05$). The histograms are the results of a calculation using JETSET [10], in which the total c.m.s energy of the $e^-e^+$ system is taken to be 10 GeV, and the highest value for the trust is taken to be 0.76, in according with the data given in [1].

Fig. 4. The energy flow is plotted as function of the pseudo-rapidity $\eta^*$ with respect to the $\gamma^*-q\bar{q}$ axis in the center of mass system of $\gamma^*-q\bar{q}$. The curves are the calculated results for quark anti-quark fragmentation using JETSET [10]. Here, integration has been performed in the corresponding $M_X$ regions when the energy-flow at each given $M_X$ is weighted by the factor $1/M_X^2$ (which is known [18] to be the characteristic $M_X$-distribution in diffractive scattering). Note that, according to the data [1], the mean thrust should be 0.7 for the first, 0.75 for the second and 0.82 for the third $M_X$-region. This piece of experimental fact has also been taken into account in the present calculation. The data are from [1].

Fig. 5. Proton diffractive dissociation $pp \to (\Lambda K^+)p$, where the produced $K^+$ is observed on the right-hand-side of the $p + p$ collision axis. (The conclusion that the $\Lambda$ is negatively polarized with respect to the production plane is of course independent of the fact, whether the $K^+$ is observed on the right-hand-side. See text for more details.)
Fig. 6. Two possibilities to produce the final state: (i) Both Λ and $K^+$ are produced by the valence-quarks of the projectile. Here $K^+$ compensates both the transverse momentum and the spin of Λ. (ii) One of the produced pions takes over the role of $K^+$ in compensating the transverse momentum and the spin of the Λ.

Fig. 7. The probability $P(h_\Lambda = -h_{\bar{\Lambda}})$ for the observed Λ in one hemisphere and the observed $\bar{\Lambda}$ in the other hemisphere in a given event are correlated, in the sense that they have opposite helicities, is plotted as a function of $(x_F)_{cut}$. Here, $(x_F)_{cut}$ is the minimum of the magnitude of the $x_F$ of Λ and that of $\bar{\Lambda}$. 
$g \rightarrow f$ 
$g \rightarrow \bar{f}$ 

$f = u, d, s, c, \ldots$
\[ \sigma_T (\gamma p \to \rho^0 p) + \sigma_L (\gamma p \to \rho^0 p) \, (\mu b) \]

- **H1 1994**: \( Q^2 \) (GeV^2) - 5.9, 8.3, 12, 20
- **ZEUS 1994**: \( x_B = 0.0005 - 0.006 \)

**Graphical Data**

- \( W \) (GeV) vs. \( \sigma_T (\gamma p \to \rho^0 p) + \sigma_L (\gamma p \to \rho^0 p) \) (\( \mu b \))

- Points correspond to different \( Q^2 \) values indicated.
\[ \frac{1}{N_{\text{evt}}} \frac{d\text{n}}{dx_F} (q \bar{q}) \gamma^* \]
\( \langle p_{\perp}^2 \rangle \) (GeV/c)^2 vs. \( x_F \)
$3\text{(GeV)} < M_x < 8\text{(GeV)}$

$8\text{(GeV)} < M_x < 18\text{(GeV)}$

$18\text{(GeV)} < M_x < 30\text{(GeV)}$
\[ \vec{n} = \frac{\vec{p}_B \times \vec{p}_\Lambda}{|\vec{p}_B \times \vec{p}_\Lambda|} \]

\[ \Lambda(\downarrow) = (ud)_v(0)s_s(\downarrow) \]

\[ \vec{p}_k \]

\[ K^+(0) = u_v(\downarrow)s_s(\uparrow) \]
$p^+ (gg) \rightarrow (\Lambda \ k^+)$
\[
p + (gg) \rightarrow (\Lambda^{k^+} + \pi^+ + \pi^- + \pi^+ + \pi^-)
\]

Diagram:

\[
p + (gg) \rightarrow (\Lambda + \pi^+ + k^+ + \pi^- + \pi^+ + \pi^-)
\]
$P(h_\Lambda = -h_\bar{\Lambda})$