CHIRAL QUARK MODEL SPIN FILTERING MECHANISM
AND HYPERON POLARIZATION

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The model combined with unitarity and impact parameter picture provides simple mechanism for generation of hyperon polarization in collision of unpolarized hadrons. We concentrate on a particular problem of Λ-hyperon polarization and derive its linear $x_F$-dependence as well as its energy and transverse momentum independence at large $p_\perp$ values. Mechanism responsible for the single-spin asymmetries in pion production is also discussed.

One of the most interesting and persistent for a long time spin phenomena was observed in inclusive hyperon production in collisions of unpolarized hadron beams. A very significant polarization of Λ–hyperons has been discovered almost three decades ago\(^1\). Experimentally the process of Λ-production has been studied more extensively than other hyperon production processes. Therefore we will emphasize on the particular riddle of Λ–polarization because spin structure of this particle is most simple and is determined by strange quark only. This mechanism can also be used for the explanation of single-spin asymmetries in the inclusive pion production.

It should be noted that understanding of transverse single-spin asymmetries in DIS (in contrast to the hyperon polarization) has observed significant progress during last years; this progress is related to an account of final-state interactions from gluon exchange\(^2,3\) – coherent effect not suppressed in the Bjorken limit.

Experimental situation with hyperon polarization is widely known and stable for a long time. Polarization of Λ produced in the unpolarized inclusive $pp$-interactions is negative and energy independent. It increases linearly with $x_F$ at large transverse momenta ($p_\perp \geq 1$ GeV/c), and for such values of transverse momenta is almost $p_\perp$-independent\(^1\).

On the theoretical side, perturbative QCD with a straightforward collinear factorization scheme leads to small values of Λ–polarization \(^4,5\)
which are far below of the corresponding experimental data. Modifications of this scheme and account for higher twists contributions allows to obtain higher magnitudes of polarization but do not change a decreasing dependence proportional to $p_{\perp}^{-1}$ at large transverse momenta\textsuperscript{6,7,8}. It is difficult to reconcile this behavior with the flat experimental data dependence on the transverse momenta. Inclusion of the internal transverse momentum of partons ($k_{\perp}$–effects) into the polarizing fragmentation functions leads to similarly decreasing polarization\textsuperscript{9}. In addition it should be noted that the perturbative QCD has also problems in the description of the unpolarized scattering, e.g. in inclusive cross-section for $\pi^0$-production, at the energies lower than the RHIC energies\textsuperscript{10}.

The essential point of the approaches mentioned above is that the vacuum at short distances is taken to be a perturbative one. There is another possibility. It might happen that the polarization dynamics in strangeness production originates from the genuine nonperturbative sector of QCD (cf. e.g.\textsuperscript{11}). In the nonperturbative sector of QCD the two important phenomena, confinement and spontaneous breaking of chiral symmetry ($\chi$SB)\textsuperscript{12} should be reproduced. The relevant scales are characterized by the parameters $\Lambda_{QCD}$ and $\Lambda_{\chi}$, respectively. Chiral $SU(3)_L \times SU(3)_R$ symmetry is spontaneously broken at the distances in the range between these two scales. The $\chi$SB mechanism leads to generation of quark masses and appearance of quark condensates. It describes transition of current into constituent quarks. Constituent quarks are the quasiparticles, i.e. they are a coherent superposition of bare quarks, their masses have a magnitude comparable to a hadron mass scale. Therefore hadron is often represented as a loosely bounded system of the constituent quarks. These observations on the hadron structure lead to understanding of several regularities observed in hadron interactions at large distances. It is well known that such picture provides reasonable values for the static characteristics of hadrons, for instance, their magnetic moments. The other well known direct result is appearance of the Goldstone bosons.

The most recent approach to single–spin asymmetries (SSA) based on nonperturbative QCD has been developed in\textsuperscript{13} where, in particular, $\Lambda$-polarization has been related to the large magnitude of the transverse flavor dipole moment of the transversely polarized baryons in the infinite momentum frame. It is based on the parton picture in the impact parameter space and assumed specific helicity–flip generalized parton distribution.

The instanton–induced mechanism of SSA generation was considered in\textsuperscript{14,15} and relates those asymmetries with a genuine nonperturbative QCD
interaction. It should be noted that the physics of instantons (cf. e.g.\textsuperscript{16}) can provide microscopic explanation for the $\chi$SB mechanism.

We discuss here mechanism for hyperon polarization based on chiral quark model\textsuperscript{12} and the filtering spin states related to unitarity in the $s$-channel. This mechanism connects polarization with asymmetry in the position (impact parameter) space.

As it was already mentioned constituent quarks and Goldstone bosons are the effective degrees of freedom in the chiral quark model. We consider a hadron consisting of the valence constituent quarks located in the central core which is embedded into a quark condensate. Collective excitations of the condensate are the Goldstone bosons and the constituent quarks interact via exchange of Goldstone bosons; this interaction is mainly due to a pion field which is of the flavor– and spin–exchange nature. Thus, quarks generate a strong field which binds them\textsuperscript{18}.

At the first stage of hadron interaction common effective self-consistent field is appeared. Valence constituent quarks are scattered simultaneously (due to strong coupling with Goldstone bosons) and in a quasi-independent way by this effective strong field. Such ideas were already used in the model\textsuperscript{19} which has been applied to description of elastic scattering and hadron production\textsuperscript{20}.

The initial state particles (protons) are unpolarized. It means that states with spin up and spin down have equal probabilities. The main idea of the proposed mechanism is the filtering of the two initial spin states of equal probability due to different strength of interactions. The particular mechanism of such filtering can be developed on the basis of chiral quark model, formulas for inclusive cross section (with account for the unitarity)\textsuperscript{21} and notion on the quasi-independent nature of valence quark scattering in the effective field.

We will exploit the feature of chiral quark model that constituent quark $Q_\uparrow$ with transverse spin in up-direction can fluctuate into Goldstone boson and another constituent quark $Q'_\downarrow$ with opposite spin direction, i. e. perform a spin-flip transition\textsuperscript{17}:

$$Q_\uparrow \rightarrow GB + Q'_\downarrow \rightarrow Q + Q' + Q'_\downarrow.$$

An absence of arrows means that the corresponding quark is unpolarized. To compensate quark spin flip $\delta S$ an orbital angular momentum $\delta L = -\delta S$ should be generated in final state of reaction (1). The presence of this

\textsuperscript{a}It has been successfully applied for the explanation of the nucleon spin structure\textsuperscript{17}. 
orbital momentum $\delta \mathbf{L}$ in its turn means shift in the impact parameter value of the final quark $Q'_\downarrow$ (which is transmitted to the shift in the impact parameter of $\Lambda$)

$$\delta \mathbf{S} \Rightarrow \delta \mathbf{L} \Rightarrow \delta \tilde{b}.$$ 

Due to different strengths of interaction at the different values of the impact parameter, the processes of transition to the spin up and down states will have different probabilities which leads eventually to polarization of $\Lambda$.

$$U^\uparrow \rightarrow K^+ + S'_\downarrow \Rightarrow -\delta \tilde{b}$$

$$U^\downarrow \rightarrow K^+ + S'_\uparrow \Rightarrow +\delta \tilde{b}.$$ (2)

Eqs. (2) clarify mechanism of the filtering of spin states: when shift in impact parameter is $-\delta \tilde{b}$ the interaction is stronger compared to the case when shift is $+\delta \tilde{b}$, and the final $S$-quark (and $\Lambda$-hyperon) is polarized negatively. Thus, the particular mechanism of filtering of spin states is related to the emission of Goldstone bosons by constituent quarks.

In a particular case of $\Lambda$–polarization the relevant transitions of constituent quark $U$ (cf. Fig. 1) will be correlated with the shifts $\delta \tilde{b}$ in impact parameter $\tilde{b}$ of the final $\Lambda$-hyperon, i.e.:

$$U^\uparrow \rightarrow K^+ + S'_\downarrow \Rightarrow -\delta \tilde{b}$$

$$U^\downarrow \rightarrow K^+ + S'_\uparrow \Rightarrow +\delta \tilde{b}.$$ (2)

It is important to note here that the shift of $\tilde{b}$ (the impact parameter of final hyperon) is translated to the shift of the impact parameter of the initial particles according to the relation between impact parameters in the multiparticle production$^{22}$:

$$b = \sum_i x_i \tilde{b}_i.$$ (3)

The variable $\tilde{b}$ is conjugated to the transverse momentum of $\Lambda$, but relations between functions depending on the impact parameters $b_i$ are nonlinear. We
consider production of Λ in the fragmentation region, i.e. at large \( x_F \) and therefore use approximate relation

\[
b \simeq x_F \hat{b},
\]

which results from Eq. (3)\(^b\).

The explicit formulas for inclusive cross-sections of the process

\[
h_1 + h_2 \rightarrow h_3 + X,
\]

where hadron \( h_3 \) is a hyperon whose transverse polarization is measured were obtained in 21. The main feature of this formalism is an account of unitarity in the direct channel of reaction. The corresponding formulas have the form

\[
d\sigma^{\uparrow,\downarrow}/d\xi = 8\pi \int_0^\infty db I^{\uparrow,\downarrow}(s, b, \xi)/|1 - iU(s, b)|^2,
\]

where \( b \) is the impact parameter of the initial particles. Here the function \( U(s, b) \) is the generalized reaction matrix (for unpolarized scattering) which is determined by the basic dynamics of elastic scattering.

The functions \( I^{\uparrow,\downarrow} \) in Eq. (5) are related to the functions \( |U_n|^2 \), where \( U_n \) are the multiparticle analogs of the \( U \)(cf. 21). The kinematical variables \( \xi (x_F, p_\perp) \) describe the state of the produced particle \( h_3 \). Arrows \( \uparrow \) and \( \downarrow \) denote transverse spin directions of the final hyperon \( h_3 \).

Polarization can be expressed in terms of the functions \( I_-, I_0 \) and \( U \):

\[
P(s, \xi) = \frac{\int_0^\infty db I_-(s, b, \xi)/|1 - iU(s, b)|^2}{2 \int_0^\infty db I_0(s, b, \xi)/|1 - iU(s, b)|^2},
\]

where \( I_0 = 1/2(I^\uparrow + I^\downarrow) \) and \( I_- = (I^\uparrow - I^\downarrow) \).

On the basis of the described chiral quark filtering mechanism we can assume that the functions \( I^\uparrow(s, b, \xi) \) and \( I^\downarrow(s, b, \xi) \) are related to the functions \( I_0(s, b, \xi)|_{\hat{b}+\delta \hat{b}} \) and \( I_0(s, b, \xi)|_{\hat{b}-\delta \hat{b}} \), respectively, i.e.

\[
I_-(s, b, \xi) = I_0(s, b, \xi)|_{\hat{b}+\delta \hat{b}} - I_0(s, b, \xi)|_{\hat{b}-\delta \hat{b}} = 2 \frac{\delta I_0(s, b, \xi)}{\delta \hat{b}} \delta \hat{b}. \]

We can connect \( \delta \hat{b} \) with the radius of quark interaction \( r_{U_S}^{\text{tip}} \) responsible for the transition \( U^\uparrow \rightarrow S_\downarrow \) changing quark spin and flavor:

\[
\delta \hat{b} \simeq r_{U_S}^{\text{tip}}.
\]

\(^b\)We make here an additional assumption on the small values of Feynman \( x \) for other particles
The following expression for polarization $P_\Lambda(s, \xi)$ can be obtained

$$P_\Lambda(s, \xi) \simeq x_F r_{U \rightarrow S} \frac{\int_0^\infty db I_0'(s, b, \xi) db}{\int_0^\infty db I_0(s, b, \xi)/|1 - iU(s, b)|^2},$$

(8)

where $I_0'(s, b, \xi) = dI_0(s, b, \xi)/db$.

It is clear that polarization of $\Lambda$-hyperon (8) should be negative because $I_0'(s, b, \xi) < 0$.

The generalized reaction matrix $U(s, b)$ (in a pure imaginary case) is the following

$$U(s, b) = i \tilde{U}(s, b) = ig(s) \exp(-Mb/\zeta),$$

(9)

$M$ is the total mass of $N$ constituent quarks with mass $m_Q$ in the initial hadrons; $\alpha$ and $g_0$ are the parameters of model. Parameter $\zeta$ is the one which determines a universal scale for the quark interaction radius, i.e. $r_Q = \zeta/m_Q$. To evaluate polarization dependence on $x_F$ and $p_\perp$ we use semiclassical correspondence between transverse momentum and impact parameter values. Choosing the region of small $p_\perp$ we select the large values of impact parameter and therefore we have

$$P_\Lambda(s, \xi) \propto -x_F r_{U \rightarrow S} M \frac{\int_{b > R(s)} db I_0(s, b, \xi) \tilde{U}(s, b)}{\int_{b > R(s)} db I_0(s, b, \xi)},$$

(10)

where $R(s) \propto \ln s$ is the hadron interaction radius, which serve as a scale of large and small impact parameter values. At large values of impact parameter $b$: $\tilde{U}(s, b) \ll 1$ for $b \gg R(s)$ and therefore we will have small polarization $P_\Lambda \simeq 0$ in the region of small and moderate $p_\perp \leq 1$ GeV/c. At small values of $b$ (and large $p_\perp$): $\tilde{U}(s, b) \gg 1$ and the following approximate relations are valid

$$\int_{b < R(s)} db I_0(s, b, \xi) \tilde{U}(s, b) \left[1 + \tilde{U}(s, b)\right]^{-3} \simeq \int_{b < R(s)} db I_0(s, b, \xi) \tilde{U}(s, b)^{-2},$$

(11)

since we can neglect unity in the denominators of the integrands. Thus, the energy and $p_\perp$-independent behavior of polarization $P_\Lambda$ takes place at large values of $p_\perp$:

$$P_\Lambda(s, \xi) \propto -x_F r_{U \rightarrow S} M/\zeta.$$  

(12)

This flat transverse momentum dependence results from the similar rescattering effects for the different spin states. The numeric value of polarization $P_\Lambda$ can be large: there are no small factors in (12). In (12) $M$ is proportional to two nucleon masses, the value of parameter $\zeta \simeq 2$. We expect that...
$r_{U \rightarrow S}^{\uparrow \uparrow} \approx 0.1 - 0.2$ fm on the basis of the model$^{19,21}$, however, this is a crude estimate. The above qualitative features of polarization dependence on $x_F$, $p_\perp$ and energy are in a good agreement with the experimentally observed trends$^3$. For example, Fig. 2 demonstrates that the linear $x_F$ dependence is in a good agreement with the experimental data in the fragmentation region ($x_F \geq 0.4$) where the model should work. Of course, the conclusion on the $p_\perp$-independence of polarization is a rather approximate one and deviation from such behavior cannot be excluded.

The proposed mechanism deals with effective degrees of freedom and takes into account collective aspects of QCD dynamics. Together with unitarity, which is an essential ingredient of this approach, it allows to obtained results for polarization dependence on kinematical variables in agreement with the experimental behavior of $\Lambda$-hyperon polarization, i.e. linear dependence on $x_F$ and flat dependence on $p_\perp$ at large $p_\perp$ in the fragmentation region are reproduced. Those dependencies together with the energy independent behavior of polarization at large transverse momenta are the straightforward consequences of this model. We discussed here particle production in the fragmentation region. In the central region where correlations between impact parameter of the initial and impact parameters of the final particles being weakened, the polarization cannot be generated due to chiral quark filtering mechanism. Moreover, it is clear that since antiquarks are produced through spin-zero Goldstone bosons we should expect $P_\Lambda \simeq 0$. The chiral quark filtering is also relatively suppressed when compared to direct elastic scattering of quarks in effective field and therefore should not play a role in the reaction $pp \rightarrow pX$ in the fragmentation region, i.e. protons should be produced unpolarized. These features take place in the experimental data set. The application of this mechanism to description of polarization of other hyperons is more complicated problem, since they
could have two or three strange quarks and spins of $U$ and $D$ quarks can also make contributions into their polarizations. Finally, it was shown that the mechanism reversed to chiral quark filtering can provide description of the SSA in $\pi^0$ production measured at FNAL and recently at RHIC in the fragmentation region and it leads to the energy independence of the asymmetry.

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