

Polarization of cascade hyperons and antihyperons

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Abstract. Polarizations of cascade hyperons (Ξ^0 and Ξ^-) and antihyperons are especially interesting because they are very sensitive to the mechanism of their production. Hyperon polarization for existing data is considered in framework of the model of chromomagnetic polarization of quarks (CPQ). Hyperon and antihyperon polarization predictions are presented for a wide range of c.m.s. energy \sqrt{s} and Feynman variable x_F .

1. Introduction

In this work, we consider the transverse polarization (P_N) of the cascade hyperons Ξ^- and Ξ^0 , and the corresponding antihyperons, that are produced in proton-nuclear interactions in inclusive reactions. The polarization of cascade hyperons and antihyperons is especially interesting in that it is very sensitive to the mechanism of formation of these particles. Hyperon polarization is considered within the framework of the model of chromomagnetic polarization of quarks (CPQ) [1-6]. According to the model, in these processes a strong chromomagnetic field is formed in the interaction region due to the motion of a large number of strange spectator quarks or antiquarks.

An active test quark, which will be part of the observed hyperon, experiences the Stern-Gerlach force in the chromomagnetic field and spin precession. As a result, the polarization of the observed hyperon is expected to oscillate, depending on the Feynman variable x_F . This is the main feature of the CPQ model, which can be tested in the upcoming SPASCHARM experiment at the NRC "Kurchatov Institute" - IHEP and in other experiments. Currently available world experimental data are compared with the results of calculations in the framework of the CPQ model. Detailed calculations of P_N were made in the kinematic regions not yet explored.

2. Model of chromomagnetic polarization of quarks

The CPQ model can be considered as a generalization of the empirical laws found during global polarization data analysis, as well as a number of ideas related to the interaction of quarks in the region of quark confinement. The mechanism underlying the model is today only one of the possible, along with other options for the generation of polarization phenomena. For further research, it is necessary, first of all, to experimentally verify the results of calculations of the single-spin asymmetry of hadrons and polarization of hyperons using this model, which differ significantly from predictions in other models. The main assumptions of the model are described in [1]. Individual reactions and features of the mechanism are considered in details in [2-6]. The CPQ model is based on the following key points:

1) After the initial color recharging of the colliding hadrons, a longitudinal chromoelectric field \mathbf{E}^a and a circular transverse chromomagnetic field \mathbf{B}^a emerge in the interaction region on

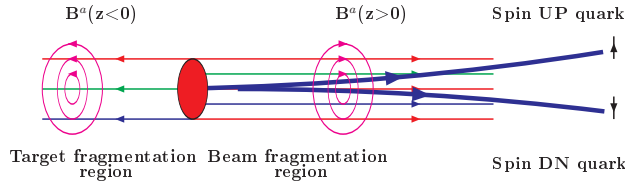


Figure 1. The mechanism of chromomagnetic polarization of quarks (Stern-Gerlach microscopic apparatus). The test quark deviates to the left or right in the inhomogeneous field \mathbf{B}^a , depending on the direction of its spin with respect to the normal to the plane of hyperon production. Circular transverse chromomagnetic field \mathbf{B}^a is created by spectator quarks and antiquarks, moving in the c.m.s. in the forward and backward directions.

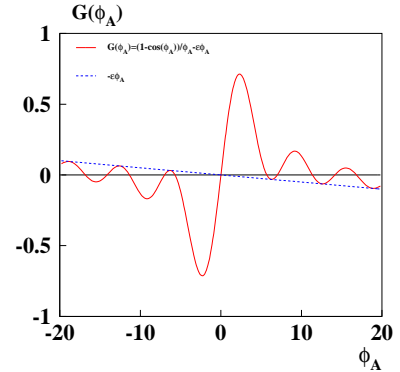


Figure 2. Dependence of the function $G(\phi_A)$ on the integral angle of the quark spin precession.

a short time.

2) The transverse polarization is due to the action of the Stern-Gerlach force on the constituent quark with the spin directed up or down in the inhomogeneous field \mathbf{B}^a . Active quarks deviate left or right in an inhomogeneous field, depending on their initial spin direction, which leads to the transverse polarization of quarks and hyperons consisting of them. In a weak color field when the precession of the quark spin is insignificant, the resulting dependence $P_N(x_F)$ is close to linear.

3) The spin precession of a polarized quark in the color field \mathbf{B}^a changes the components of the Stern-Gerlach force acting on it, which affects the magnitude and sign of transverse polarization of quarks and leads, in the case of a strong color field, to a nonmonotonic (oscillating) dependence $P_N(x_F)$ for hyperons consisting of them.

4) Quark flow diagrams and calculation rules for spectator quarks (passive quarks not included in the observed hadron) describe the contribution of quarks and antiquarks to the effective chromomagnetic field \mathbf{B}^a . Contribution of quark- and antiquark-spectators to the field \mathbf{B}^a is a linear function of their number with weights determined by the color coefficients $C_F(qq)$ and $C_F(q\bar{q})$ for the corresponding pair of quarks, as well as an additional parameter τ , which takes into account the direction of motion of the spectator quark in the reaction c.m.s. One of the quarks of the pair is active and is part of the observed hyperon, and the other is a passive spectator, which creates the field \mathbf{B}^a .

The mechanism for the generation the transverse polarization of hyperons is shown schematically in Fig. 1. The initial region of hadron interaction in the c.m.s. is shown in Fig. 1 in red. Spectator quarks and active quarks (which will be part of the observed hyperon) fly out of this region. Also shown is a circular chromomagnetic field \mathbf{B}^a created by moving relativistic spectator quarks.

The direction of the emerging transverse circular chromomagnetic field \mathbf{B}^a depends on the direction of motion of the quark- and antiquark-spectators in the reaction c.m.s. Usually it is directed oppositely in the fragmentation region of the incident particle and the target, respectively. We can say that moving spectator quarks form a color current, which, in turn, creates a circular transverse chromomagnetic field similar to the magnetic field created by moving electrons. The model parameters were estimated from a global analysis of polarization data for 81 inclusive reactions with a total number of experimental points of 3671 [1-6].

Transverse polarization of hyperons (P_N) is described by equations (1) and (2):

$$P_N = C(\sqrt{s})F(p_T, A)[G(\phi_A) - \sigma G(\phi_B)], \quad (1)$$

$$G(\phi) = (1 - \cos \phi)/\phi + \epsilon \cdot \phi, \quad (2)$$

where the function $G(\phi)$ is the result of the action of the Stern-Gerlach force on the active quark and the simultaneous precession of its spin (see Fig. 2) [1]. The variables ϕ_A and ϕ_B are the integral angles of the precession of the quark spin in the fragmentation region of the incident particle A and target B , respectively, considered in the reaction c.m.s. The parameter $\epsilon = -0.00497 \pm 0.00009$ was found from the global analysis of polarization data [1]. Oscillations of the function $G(\phi)$ lead to a nonmonotonic (oscillating) dependence of $P_N(x_F)$.

The variables ϕ_A and ϕ_B are expressed in terms of the model parameters and kinematic variables according to the equations:

$$\phi_A = \omega_A^0 y_A, \quad \phi_B = \omega_B^0 y_B, \quad (3)$$

$$\omega_{A(B)}^0 \propto \nu_{A(B)}, \quad (4)$$

$$y_A = x_A - (E_0/\sqrt{s} + f_0)[1 + \cos \theta_{cm}] + a_0[1 - \cos \theta_{cm}], \quad (5)$$

$$y_B = x_B - (E_0/\sqrt{s} + f_0)[1 - \cos \theta_{cm}] + a_0[1 + \cos \theta_{cm}], \quad (6)$$

$$x_A = (x_R + x_F)/2, \quad x_B = (x_R - x_F)/2. \quad (7)$$

The radial scaling variable x_R is defined as the ratio of the particle momentum to its possible maximum value in the c.m.s. of the reaction. Equation (4) includes the global parameters of the CPQ model, known with high accuracy [1-6]. Equations (5) and (6) depend on the kinematic variables and on the local parameters of the CPQ model (E_0, f_0, a_0) associated with a specific reaction [1]. In particular, \sqrt{s} is the total reaction energy, and θ_{cm} is the angle of hadron production in the c.m.s.

An important variable in (4) is $\nu_{A(B)}$, which is the effective (weighted) contribution of the spectator quarks to the magnitude of the chromomagnetic field \mathbf{B}^a . To calculate $\nu_{A(B)}$, it is necessary to draw a diagram of the quark flux for the corresponding reaction.

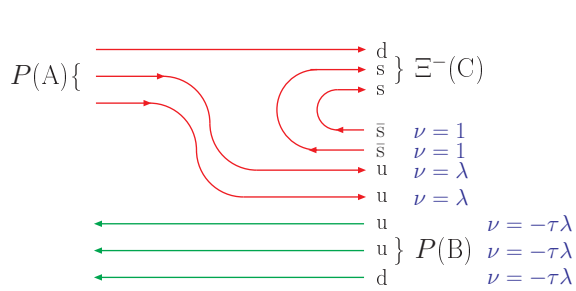


Figure 3. Quark flux diagram for the reaction $p + p \rightarrow \Xi^- + X$.

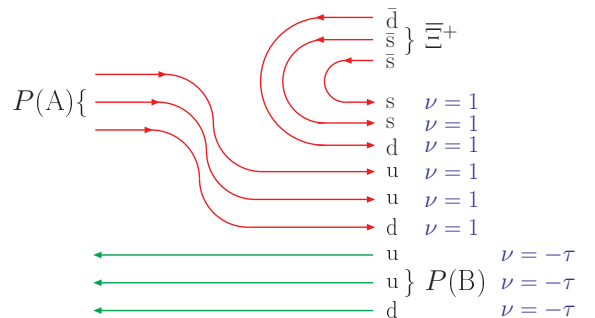


Figure 4. Quark flux diagram for the reaction $p + p \rightarrow \Xi^+ + X$.

In Fig. 3 is shown a diagram for the reaction $p + p \rightarrow \Xi^- + X$, and for comparison in Fig. 4 is shown a diagram for the reaction $p + p \rightarrow \Xi^+ + X$. To the right of the quark flow diagram there is shown the weighted contribution ν of each quark- or antiquark-spectator to the field \mathbf{B}^a . The rules for counting quarks tell us that the weight ν is equal to λ if the active quark from a hyperon

interacts with passive spectator quark. If an active quark interacts with an antiquark-spectator, then the weight ν is 1. For the spectator quark from the target, an additional negative factor $-\tau$ appears, since this quark moves in the opposite direction in the reaction c.m.s., and the field \mathbf{B}^a it creates in the backward hemisphere weakly affects the active quark moving forward.

The values $\lambda = -0.1363 \pm 0.0003$ and $\tau = 0.0267 \pm 0.0005$ were obtained from the global fit of 81 polarization reactions. Thus, λ is the ratio of contributions to the field \mathbf{B}^a of the interactions qq and $q\bar{q}$. The negative sign of λ follows from the opposite sign of the field created by the quark and antiquark. The magnitude of λ as a first approximation can be estimated as the ratio of the probabilities of finding the pairs qq and $q\bar{q}$ in the antitriplet and singlet state by color:

$$\lambda \approx -|\Psi_{qq}(0)|^2/|\Psi_{q\bar{q}}(0)|^2 = -1/8, \quad (8)$$

since for the wave function of qq ($q\bar{q}$): $|\Psi(0)|^2 \propto (C_F)^3$, $C_F(qq) = 2/3$ and $C_F(q\bar{q}) = 4/3$ [7,1].

Summing up the contributions of all spectator quarks shown to the right of the diagrams, we obtain $\nu_A = 2(1+\lambda) - 3\tau\lambda$, $\nu_B = 3\lambda - 2\tau(1+\lambda)$ for the reaction $p+p \rightarrow \Xi^- + X$ and $\nu_A = 6 - 3\tau$, $\nu_B = 3 - 6\tau$ for the reaction $p+p \rightarrow \Xi^+ + X$. The significant value of ν_A for cascade hyperons and antihyperons should lead to nonmonotonicity (oscillations) in the behavior of $P_N(x_F)$.

3. Polarization data for cascade hyperons Ξ^- and Ξ^0

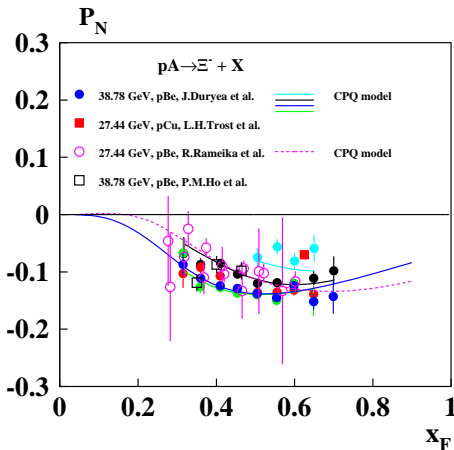


Figure 5. Polarization data $P_N(x_F)$ for the reaction $p + A \rightarrow \Xi^- + X$ [8, 9, 10, 11].

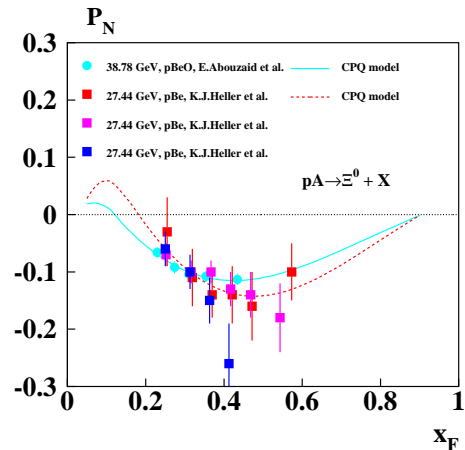


Figure 6. Polarization data $P_N(x_F)$ for the reaction $p + A \rightarrow \Xi^0 + X$ [12, 13].

The polarization data for the reaction $p + A \rightarrow \Xi^- + X$ are shown in Fig. 5 [8, 9, 10, 11], and for $p + A \rightarrow \Xi^0 + X$ in Fig. 6 [12, 13]. From Fig. 5 and 6 it can be seen that $P_N(x_F)$ for cascade hyperons is not monotonous (it oscillates). This is consistent with the predictions of the CPQ model shown by the corresponding curves.

4. Polarization data for cascade antihyperons $\bar{\Xi}^+$ and $\bar{\Xi}^0$

The available data on the polarization of cascade antihyperons [11, 12] are shown in Figs. 7 and 8. From Figs. 7 and 8 it can be seen that the polarization of $P_N(x_F)$ of cascade antihyperons generated in pA collisions oscillates with a higher frequency than in the case of the corresponding hyperons. The calculations of the CPQ model are consistent with the data and predict several peaks for the $P_N(x_F)$ dependence. This is the main signature of the CPQ model.

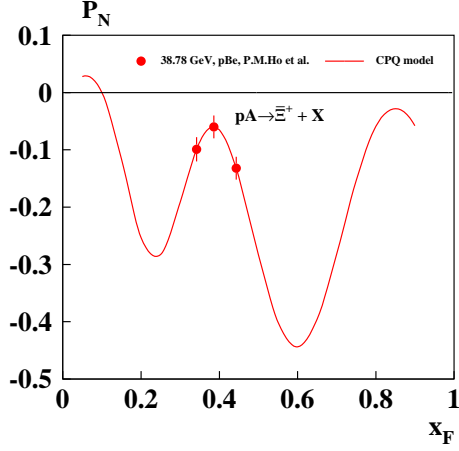


Figure 7. Polarization data $P_N(x_F)$ for the reaction $p + A \rightarrow \Xi^+ + X$ [11].

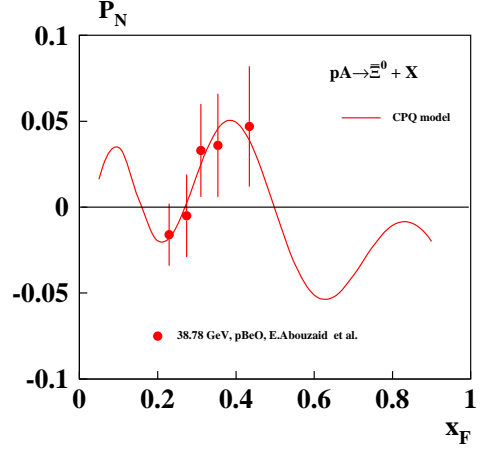


Figure 8. Polarization data $P_N(x_F)$ for the reaction $p + A \rightarrow \Xi^0 + X$ [12].

5. Calculations of the polarization of cascade hyperons and antihyperons

The $P_N(x_F)$ calculations for the reactions $p + A \rightarrow \Xi^- + X$ and $p + A \rightarrow \Xi^0 + X$ are shown in Figs. 9 and 10 for $p_T = 1.2$ GeV/c (near the maximum of $|P_N(x_F, p_T)|$). Polarization calculations

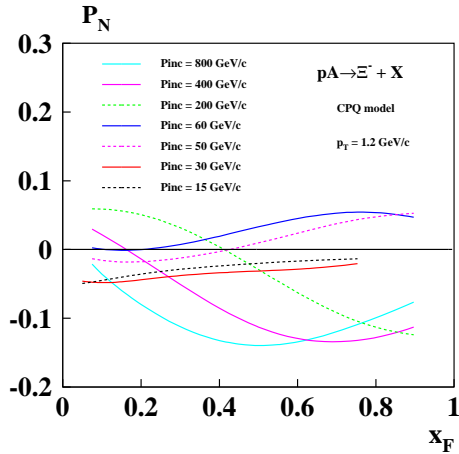


Figure 9. Calculations of $P_N(x_F)$ for the reaction $p + A \rightarrow \Xi^- + X$.

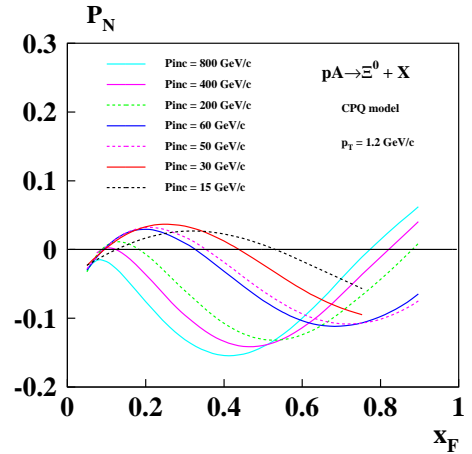


Figure 10. Calculations of $P_N(x_F)$ for the reaction $p + A \rightarrow \Xi^0 + X$.

$P_N(x_F)$ for the reactions $p + A \rightarrow \Xi^+ + X$ and $p + A \rightarrow \Xi^0 + X$ are shown in Figs. 11 and 12 for $p_T = 0.7$ GeV/c (near the maximum of $|P_N(x_F, p_T)|$). As the beam momentum increases, the peak position for $P_N(x_F)$ moves to the region of lower values of x_F . The oscillation $P_N(x_F)$ is the main prediction of the CPQ model and is due to the precession of the quark spin in a strong chromomagnetic field.

Conclusions and outlook

- 1) The existing $P_N(x_F)$ polarization data for cascade hyperons and antihyperons indicate nonmonotonic (oscillating) behavior depending on x_F . This feature of the data is explained and reproduced in the framework of the model of chromomagnetic polarization of quarks

(CPQ). To detect oscillations in $P_N(x_F)$, measurements must be performed over a wide range of x_F . The oscillation of $P_N(x_F)$ is the main signature of the CPQ model.

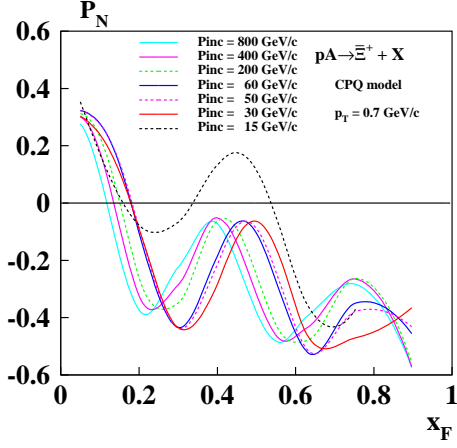


Figure 11. Calculations of $P_N(x_F)$ for the reaction $p + A \rightarrow \bar{\Xi}^+ + X$.

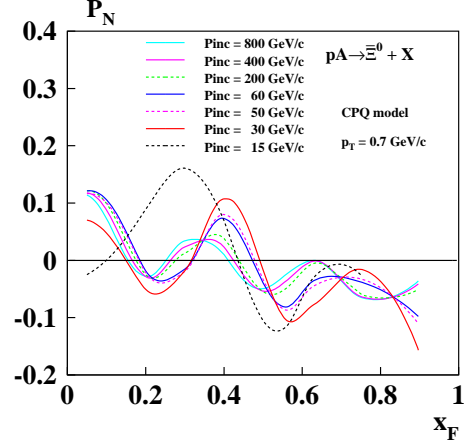


Figure 12. Calculations of $P_N(x_F)$ for the reaction $p + A \rightarrow \bar{\Xi}^0 + X$.

- 2) In the CPQ model, the oscillation of $P_N(x_F)$ is expected due to the quark spin precession in a strong circular transverse chromomagnetic field, which exists for a short time in the nucleon interaction region.
- 3) The oscillation frequency of $P_N(x_F)$ is proportional to the number of quark (antiquark) spectators, ν_A and ν_B , with weights depending on the color factor (λ) and a parameter that takes into account the direction of motion (τ) of the spectator quarks in the c.m.s.
- 4) Quark flux diagrams can be used to estimate the effective number of spectator quarks ν_A and ν_B , which depend also on atomic weight and kinematic variables (at high energy).
- 5) The calculations of the cascade hyperon polarization within the framework of the CPQ model can be verified in the experiments SPASCHARM (IHEP), SPD (JINR), STAR, and PHENIX (BNL).

Acknowledgments

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