Spin measurements in strangeness production
at the LHC

S.M. Troshin, N.E. Tyurin

SRC IHEP of NRC “Kurchatov Institute”
Protvino, 142281, Russian Federation

Abstract

We briefly recollect the problem of significant hyperon polarization emphasizing the role of spin in dynamics of hadron interactions. We provide also some model predictions based on chiral dynamics and the impact parameter picture for illustration. The old, but yet unsolved problem of hyperon polarization, can obtain a new insight from the measurements at the LHC energies and, in combination with other measurements, can be used for tagging QGP formation in $pp$–collisions.
Introduction

The importance of spin measurements for studies of hadron–interaction dynamics is well known. However, there are very few well established experimental facts regarding behavior and dependence of spin observables at high energies. In particular, the knowledge of the energy dependence of such observables is crucial for the analysis since it could justify, neglecting the spin degrees of freedom. The LHC machine provides record energy of collisions and could definitely help in this matter. The experiments at the LHC have discovered several collective effects in such small systems as \( pp \)–interactions (cf. reviews \cite{1,2} and references therein to the original papers.)

The feasible experimental direction of the spin studies is based on the self-analyzing particle decays, the mostly known example of which is the weak decay of \( \Lambda \)-hyperon (cf. e.g \cite{3}). To study energy dependence of spin effects it is most relevant to choose the respective reaction where measurements have already been performed in the widest range of energy variation, namely, the measurements of the polarization of the above mentioned final \( \Lambda \)-hyperon in the inclusive reaction \( pp \rightarrow \Lambda X \). It is the most interesting and persistent for a long time spin phenomena which was observed in inclusive hyperon production in collisions of unpolarized hadron beams. A very significant polarization of \( \Lambda \)–hyperons has been discovered more than four decades ago (cf. \cite{3} and references therein) and experimentally, the process of \( \Lambda \)-production has been studied more extensively than other hyperon production processes. Therefore, we concentrate on the particular pattern of \( \Lambda \)–polarization. In addition, the spin structure of this particle seems rather simple and is determined by spin of strange quark in the \( SU(6) \)-quark model.

Experimental results on hyperon polarization are widely known, those being stable during a long time and well documented. Polarization of \( \Lambda \) produced in the unpolarized inclusive \( pp \)–collisions is negative (it is perpendicular to production plane and directed opposite to the normal to this plane) and energy independent. It increases linearly with \( x_F \) at large transverse momenta \( (p_\perp \geq 1 \text{ GeV}/c) \), and for such values of transverse momenta is almost \( p_\perp \)-independent. The comprehensive review of the experimental situation is given in \cite{3}. It should be noted that the above results are for the hyperons which appear to be the proton’s fragmentation products. No energy independence of global polarization has been observed for \( \Lambda \)’s produced in the nuclear \( AuAu \)–interactions \cite{4}. The recent RHIC data (with high error bars, though) could imply energy decrease of global polarization of \( \Lambda \) and could testify that the different leading dynamical mechanisms result in the strange quark polarization in nuclear collisions. However, one should also take into account that the data in this case are for the polarization measured with respect to reaction (not production) plane.

Perturbative QCD amended by the collinear factorization scheme leads to van-
ishing values of $\Lambda$–polarization\cite{5,6} and does not correspond to the experimental data values and observed trends. Including the higher twists contributions allows one to obtain higher values for polarization but does not change qualitative dependence $p_{1}^{-1}$ at large transverse momenta\cite{7,8,9}. It is difficult to reconcile the decreasing dependence with the flat one observed in the data. Inclusion of the parton internal transverse momenta ($k_{\perp}$–effects) into the polarizing fragmentation functions leads also to decreasing trend of polarization\cite{10}. It allows again to change the scale only.

The aim of this note is to provide arguments for measurements of the hyperon polarization at the LHC energies. For that purpose we discuss the mechanism leading to a nondecreasing energy dependence of the transverse polarization of $\Lambda$ produced in $pp$–collisions. We also briefly present an experimental feasibility of such measurements and point out to the role of polarization studies in the strangeness production as a complementary tool for QGP detection in small systems.

1 Mechanism of the strange quark polarization

In the simple quark model the u- and d-quarks in $\Lambda$ are coupled to $S=0$, $I=0$ di-quark. It is strange quark polarization is responsible for the significant transverse polarization of $\Lambda$. Thus, to explain the $\Lambda$–polarization the dynamical mechanism of the strange quark polarization should be developed. There were several proposals for an explanation of the polarization of strange quarks produced in the collisions of the unpolarized protons. Among them one should note the mechanism based on Thomas precession\cite{11} and Lund model\cite{12}. The both explanations are semiclassical in its nature. There is another semiclassical mechanism based on chiral spin filtering. We briefly mention it in order to stress that the measurements of the final hyperon polarization at the LHC energies could have sense since this particular mechanism leads to a nonvanishing polarization of $\Lambda$ when collision energy increases.

The polarization of the strange quarks might happen to originate from a genuine nonperturbative QCD (cf. e.g.\cite{13}).

In the nonperturbative sector of QCD, there are two important phenomena, confinement and spontaneous breaking of chiral symmetry ($\chi$SB). The relevant scales are defined by the parameters $\Lambda_{QCD}$ and $\Lambda_{\chi}$. Chiral $SU(3)_{L} \times SU(3)_{R}$ symmetry is spontaneously broken at the distances which are in the range between the above 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 considered to be the quasiparticles, i.e. they are a coherent superposition of bare quarks and their masses have
a magnitude comparable to a hadron mass scale. The hadron is represented as a loosely bounded system of the constituent quarks. The well known direct result of the $\chi$SB mechanism is appearance of the Goldstone bosons (GB).

The particles (protons) in the initial state are unpolarized. Absence of polarization means that probabilities of states with spin up and spin down are equal. The main idea of the mechanism is filtering of the two initial spin states with due to different strength of interactions. This filtering acts like polaroid and leads to polarization of the particles in final state ($\Lambda$, in particular). The specific mechanism of such filtering can be developed on the basis of chiral quark model. Namely, we 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 performing a spin-flip transition [14]:

$$Q_\uparrow \rightarrow GB + Q_\downarrow' \rightarrow Q + \bar{Q}' + Q_\downarrow'.$$  

To compensate quark spin flip $\delta S$ an orbital angular momentum $\delta L = -\delta S$ should be generated in the final state of reaction (1). The presence of this orbital momentum $\delta L$ in its turn means a certain shift in the impact parameter value of the final quark $Q'_\downarrow$ (which in its turn is transmitted to the shift in the impact parameter of $\Lambda$)

$$\delta S \Rightarrow \delta L \Rightarrow \delta b_{Q'}.$$  

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 $\Lambda$.

![Diagram](image-url)

Figure 1: Transition of the spin-up constituent quark $U$ to the spin-down strange quark.

In the case of $\Lambda$–polarization, the relevant transitions of constituent quark $U$ (cf. Fig. 1) is correlated with the shifts $\delta b_S$ in impact parameter $b_S$ of the final strange quark, i.e.:

$$U_\uparrow \rightarrow K^+ + S_\uparrow \Rightarrow -\delta b_S$$
$$U_\downarrow \rightarrow K^+ + S_\uparrow \Rightarrow +\delta b_S.$$  

(2)
Relations (2) clarify the mechanism of spin states filtering: i.e. when shift in impact parameter is \(-\delta b_S\) the interaction is stronger compared to the case when shift is \(+\delta b_S\), and the final \(S\)-quark (and \(\Lambda\)-hyperon) becomes negatively polarized. The adopted mechanism of the spin states filtering is associated with the emission of Goldstone bosons by the constituent quarks.

It is important to note here that the shift of \(b_\Lambda\) (the impact parameter of the final hyperon) is correlated with the shift of the impact parameter of the initial particles according to the relation between impact parameters in the multiparticle production [15]:

\[
b = \sum_i x_i b_i. \tag{3}
\]

Let the variable \(b_\Lambda\) to be conjugated to the transverse momentum of \(\Lambda\), but relations between functions depending on the impact parameters \(b_i\) are nonlinear. Since we are considering production of \(\Lambda\) in the fragmentation region, (i.e. at large \(x_F\)) the following approximate relation

\[
b \simeq x_F b_\Lambda, \tag{4}
\]

which results from Eq. (3) \(1\) is adopted.

The main interest of this note is a trend for the polarization energy dependence, which can be checked experimentally. We note only that \(\delta b_S\) (we assume that \(\delta b_S \simeq \delta b_\Lambda\)) can be connected with the radius of quark interaction \(r_{U\rightarrow S}^{flip}\) responsible for the transition \(U \uparrow \rightarrow S \downarrow\) changing quark spin and flavor:

\[
\delta b_S \simeq r_{U\rightarrow S}^{flip}.
\]

To evaluate polarization dependence on \(x_F\) and \(p_\perp\) we use semiclassical correspondence between transverse momentum and impact parameter values. The energy and \(p_\perp\)-independent behavior of polarization \(P_\Lambda\) takes place at large values of \(p_\perp\):

\[
P_\Lambda(s, \xi) \propto -x_F r_{U\rightarrow S}^{flip} M/\zeta. \tag{5}
\]

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 since there are no small factors in (5). We use the model \([16]\) where \(M\) is proportional to two nucleon masses, the value of parameter \(\zeta \approx 2\) and \(r_{U\rightarrow S}^{flip} \approx 0.1 - 0.2\) fm. 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 \((x_F \geq 0.4)\)

\(^1\text{With an assumption on the smallness of Feynman } x_F \text{ for other secondary particles.}\)
where the model should work. Of course, the conclusion on $p_\perp$—independence of $\Lambda$-polarization is a rather approximate one and insignificant deviations from such behavior cannot be excluded.

Figure 2: $x_F$ (left panel) and $p_T$ (right panel) dependencies of the $\Lambda$-hyperon polarization

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 polarization in the 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 are weak, polarization cannot be generated due to the chiral quark filtering mechanism. It is also valid for QGP production as a result of the vacuum excitation. The transverse polarization of $\Lambda$ is expected to be zero too [3]. Thus, the detection of vanishing transverse polarization might be associated with QGP production. Of course, zeroing of transverse polarization is not sufficient to conclude on QGP formation. It is important to note in view of the recent results of the ALICE measurements [17], where the data show for the first time that the yields of strangeness increases with multiplicity compared to the yield of pions. Such enhancement at high multiplicities could be interpreted as a signal of QCP formation in small systems (cf. [17] and references therein).

The measurements performed by ATLAS Collaboration [18] at the LHC are also in favor of the above conclusion. Moreover, it is clear that since antiquarks are produced through spin-zero Goldstone bosons we should expect transverse polarization $P_{\bar{\Lambda}} \simeq 0$. The chiral quark filtering is also relatively suppressed when compared to direct elastic scattering of quarks and therefore should not play a role in the reaction $pp \rightarrow p\Lambda X$ in the fragmentation region, i.e. protons should be
produced unpolarized. Indeed, these features take place in the experimental data set.

We considered here the mechanism leading to polarization of $\Lambda$ resulting from fragmentation of a colliding proton. From this point of view it seems rather naturally to expect a large polarization of $\Lambda$ in the process of diffraction dissociation

$$p + p \rightarrow \Lambda + K^+ + X.$$ 

The measurements performed at ISR [19] are in agreement with this observation.

2 On the $\Lambda$-polarization measurements at the LHC

The results discussed in the previous section demonstrate that studies of spin effects at such high energy as the LHC provides are not senseless. Here we mention a simple experimental feasibility for performing those measurements. The measurements are based on the studies of the weak decay of $\Lambda$ into $p$ and $\pi^-$ which allows one to reconstruct $P_\Lambda$ from the angular distribution of the proton $dN/d\cos \theta_p$ produced as a result of this decay. It can be performed since this angular distribution is proportional to

$$1 + \alpha_\Lambda P_\Lambda \cos \theta_p,$$

where $\theta_p$ is the angle between the nucleon momentum and the axis of the hyperon’s polarization. Plotting the distribution $dN/d\cos \theta_p$ against $\cos \theta_p$ the polarization can be obtained since the value of the decay parameter $\alpha_\Lambda$ is known. Two-track events should be used to reconstruct $\Lambda \rightarrow p\pi^-$ weak decays and it seems promising to use T1 and T2 inelastic telescopes of the TOTEM experiment as a base for the relevant experimental set-up.

The $\Lambda$ polarization direction is parallel to the normal to the production plane $\hat{n}$. This is the result of the parity conservation in strong interactions. The unit vector $\hat{n}$ is determined by the product

$$\hat{n} = \frac{\vec{p}_b \times \vec{p}_\Lambda}{|\vec{p}_b \times \vec{p}_\Lambda|}$$

of the beam momentum $\vec{p}_b$ and $\vec{p}_\Lambda$ (momentum of $\Lambda$). In central rapidity region, the transverse polarization of $\Lambda$ has been measured at the LHC [18], where small value of it has been found.

However, polarization of $\Lambda$ in the diffraction dissociation processes is expected to be at the level 30-40% on the base of the experimental data extrapolations and simple semiclassical mechanisms’ estimations. It is important also to check an
energy independence of the hyperon polarization observed at lower energies to bring deeper understanding of the diffractive physics and its dependence on spin.

One could note that the instrumental experience obtained at CERN ISR at polarization measurements of $\Lambda$ (under the use of e.g. R608 forward spectrometer [19]) could be helpful at the LHC too, and especially in the diffractive dissociation processes.

The measurements discussed above are also important for the QGP detection. The importance of the transverse polarization measurements has already been noted. An indirect way to measure intensity of the multistrange baryon production has been earlier discussed in [3] and is based on the studies of the longitudinal polarization of $\bar{\Lambda}$ produced in the weak decay $\bar{\Xi} \to \bar{\Lambda} + \pi$ of the unpolarized $\bar{\Xi}$. This polarization arises due to parity nonconservation at this weak decay process. As it was mentioned in [3], the QGP formation might lead to a very significant longitudinal polarization of $\bar{\Lambda}$.

Finally, spin studies at the LHC are a relevant tool for the strong sector of the Standard Model test as well as these could serve one of the important probes of the QGP formation.

References

[1] S.M. Troshin, N.E. Tyurin, Int. J. Mod. Phys. A 26 4703 (2011)
[2] S. Schlichting, P. Tribedy, Adv. High Energy Phys. 2016, 8460349 (2016)
[3] A.D. Panagiotou, Int. J. Mod. Phys. 5 1197 (1990).
[4] M. Lisa (STAR Collaboration), talk at QCD Chirality Workshop, UCLA, February 2016.
[5] G.L. Kane, J. Pumplin, W. Repko, Phys. Rev. Lett. 41, 1689 (1978).
[6] W.G.D. Dharmaratna, G.R. Goldstein, Phys. Rev. D 53, 1073 (1996)
[7] A.V. Efremov, O.V. Teryaev, Sov. J. Nucl. Phys. 36, 140 (1982).
[8] J. Qiu, G. Sterman, Phys. Rev. D59, 014004 (1999).
[9] Y. Kanazawa, Y. Koike, Phys. Rev. D 64, 034019 (2001).
[10] M. Anselmino, D. Boer, U. D’Alesio., F. Murgia, Phys. Rev. D.63, 054029 (2001).
[11] T.A. DeGrand, H.I. Miettinen, Phys. Rev. D 23, 1227 (1981).
[12] B. Andersson et al., Phys. Rep. (97), 3 (1983).
[13] S.M. Troshin, N.E. Tyurin, Sov. J. Nucl. Phys. 38, 639 (1983); Phys. Lett. B 355, 543 (1995); AIP Conf. Proc. 675, 579, 2003.

[14] J.D. Bjorken, Report No. SLAC-PUB-5608, 1991 (unpublished);
    E.J. Eichten, I. Hinchliffe, C. Quigg, Phys. Rev. D, 45, 2269, 1992;
    T.P. Cheng, L.-F. Li, Phys. Rev. Lett 80, 2789 (1998).

[15] B.R. Webber, Nucl. Phys. B 87, 269 (1975).

[16] S. M. Troshin, N. E. Tyurin, Phys. Rev. D 88, 017502 (2013).

[17] J. Adam et al. (ALICE Collaboration), CERN-EP-2016-153, arXiv: 1606.07424v2.

[18] G. Aad et al. (ATLAS Collaboration), Phys. Rev. D 91, 032004 (2015).

[19] S. Erhan et al., Phys. Lett. B 84, 447 (1979).