LAMBDA POLARIZATION IN LEPTON INDUCED REACTIONS

A.M. Kotzinian

JINR, Dubna and YerPhI, Yerevan

Abstract

Different phenomenological approaches for $\Lambda$ and $\bar{\Lambda}$ polarization in polarized semi-inclusive deep inelastic scattering and electron-positron annihilation at $Z^0$ pole are considered. Current and future experiments will soon provide accurate enough data to study spin phenomena in these reactions and distinguish between various models.

Talk given at the
SPIN-97 VII Workshop on
*High Energy Spin Physics*
7-12 July 1997, Dubna, Russia.
*(to be published in the proceedings)*
The self-analysing properties of the $\Lambda(\bar{\Lambda})$ make this particle particularly suited for spin physics. Non-trivial \textit{negative} longitudinal polarization of $\Lambda$’s produced in the target fragmentation region of the deep-inelastic $\bar{\nu}$ scattering, measured with respect to the direction of the momentum transfer from the beam, has been observed in WA59 experiments [1]. These data can be interpreted in a simple way [2] by using the model of polarized intrinsic strangeness in polarized nucleon [3]. According to this model a valence quark core with (essentially) the naïve quark model spin content may be accompanied by a spin–triplet $s\bar{s}$ pair in which the $\bar{s}$ antiquark is supposed to be negatively polarized, motivated by chiral dynamics, and likewise the $s$ quark, motivated by $^3P_0$ quark condensation in the vacuum.

The essence of our argument [2] is that the right-handed polarization of the $\bar{\nu}$ beam is transferred to the hadrons via polarized $W^-$-exchange, which selects preferentially one \textit{longitudinal} polarization state of the nucleon target. Specifically, in most interactions the $\bar{\nu}$-induced $W$ removes a \textit{positively}-polarized $u$ quark from the nucleon target, as seen in Fig. 1.

In the naïve quark-parton model of deep-inelastic $\nu$ or $\bar{\nu}$ scattering, the net longitudinal polarization of a remnant $s$ quark, $P_s$, is given by

$$P_s = \frac{\sum_q c_{s,q} N_q - \sum_{\bar{q}} c_{s,\bar{q}} \bar{N}_{\bar{q}}}{N_{\text{tot}}},$$

where $c_{s,q}$ is the remnant $s$ quark spin-correlation coefficient with the struck quark $q$, $N_q$ ($\bar{N}_{\bar{q}}$) is the total number of events selected in which a quark (antiquark) is struck, and $N_{\text{tot}} = N_q + \bar{N}_{\bar{q}}$ is the total number of events selected. According to the polarized strangeness model, the polarization of the remnant $s$ quark is 100\% \textit{anticorrelated} with that of the valence quark, and 100\% \textit{correlated} with that of struck sea $\bar{s}$ antiquark (see Fig. 2):

$$c_{s u_{\text{val}}} = c_{s d_{\text{val}}} = -1,$$
$$c_{s q_{\text{sea}}} = \delta_{s,q}.$$

![Figure 1: Dominant diagram for $\Lambda$ production in the target fragmentation region due to scattering on a valence $u$ quark. Each small arrow represent the longitudinal polarization of the corresponding particle.](image1.png)

![Figure 2: Diagram for $\Lambda$ production in a $\bar{\nu} N$ event due to $W$ interaction with a $\bar{s}$ quark from the sea. As in Fig. 1, the small arrows represent longitudinal polarizations.](image2.png)
In the simple quark model the polarization of a directly-produced \( \Lambda \) is the same as that of the remnant \( s \) quark. However, final-state \( \Lambda \)'s may also be produced indirectly via the decays of heavier hyperon resonances, which tends to dilute the \( \Lambda \) polarization by a factor we denote by \( D_F \). Thus the final-state longitudinal \( \Lambda \) polarization is

\[
P_\Lambda = D_F P_s,
\]

(3)

The fraction of \( \Lambda \)'s produced indirectly may vary with the kinematical conditions, e.g., it may be higher when the invariant mass of the produced hadron system is larger.

We have used the Lund Monte Carlo program LEPTO to obtain numerical results. In the Table 1 our results for the polarization \( P_s \) of the remnant \( s \) quark in various ranges of Bjorken \( x \), together with the corresponding values of \( P_\Lambda \) measured in WA59 experiment. We also tabulate the corresponding values of \( D_F \) inferred from our calculated values of \( P_s \) and the measured values of \( P_\Lambda \).

| \( x \) range         | \( 0 < x < 1 \) | \( 0 < x < 0.2 \) | \( 0.2 < x < 1 \) |
|-----------------------|-----------------|-----------------|-----------------|
| \( P_\Lambda \) in WA59 experiment | \(-0.63 \pm 0.13\) | \(-0.46 \pm 0.19\) | \(-0.85 \pm 0.19\) |
| \( P_s \) in our model     | \(-0.86\)       | \(-0.84\)       | \(-0.94\)       |
| Dilution factor \( D_F \) | \(0.73 \pm 0.15\) | \(0.55 \pm 0.23\) | \(0.90 \pm 0.20\) |

Table 1: \( \Lambda \) polarization in the target fragmentation region \( (x_F < 0) \).

The similar value and sign of \( \Lambda \) polarization is expected also for the \( \nu \)-beam.

It is interesting to contrast the above predictions with the expectation for the meson cloud model of DIS \[4\]. In such a model the \( \Lambda \) polarisation in the target fragmentation region is expected to be zero for unpolarized target (in contradiction with WA59 data) and very strongly anticorrelated with the target polarization. In the similar light-cone meson-baryon fluctuation model \[5\] one expect the negative polarization for the produced \( \Lambda \) and zero (or slightly positive) for the produced \( \bar{\Lambda} \) whereas in our approach both polarization are expected to be negative.

Next we apply our model to predict the polarization of \( \Lambda \)'s produced in the target fragmentation region in the deep-inelastic scattering of polarized muons (electrons) on both unpolarized and polarized nucleon targets. It is easy to find the following expression for the polarization of the remnant \( s \) quark

\[
P_{s,\text{rem}} = \frac{\sum_q e_q^2 [P_T \Delta q(x) - P_B D(y) q(x)] c_s q}{\sum_q e_q^2 [q(x) - P_B P_T D(y) \Delta q(x)]},
\]

(4)

where \( P_B \) and \( P_T \) are the beam and target longitudinal polarizations, \( e_q \) is the quark charge, \( q(x) \) and \( \Delta q(x) \) are the unpolarized and polarized quark distribution functions, and \( D(y) = [1 - (1 - y)^2] / [1 + (1 - y)^2] \).

The results of our calculations for a \( \mu \) beam with the longitudinal polarization \( P_\mu = -0.8 \) are shown in Fig. 6, together with the cases \( P_\mu = 0 \) and 0.8.

The produced \( \Lambda \) polarization is given by equation (3). We concluded from our analysis of the WA59 data that in the valence-quark region the fragmentation dilution factor
Figure 3: Polarization of remnant $s$ quark for deep-inelastic $\mu$ scattering, as a function of the target polarization $P_T$ for different values of the beam polarization $P_\mu$. a) for a proton target, b) for an ammonia target. We assume $E_\mu = 190$ GeV and the following cuts were applied: $-0.3 < x_F < 0$, $0.15 < x < 0.5$, $0.5 < y < 0.9$.

$D_F \gtrsim 0.7$. Therefore, we expect large polarization effects also for $\Lambda$ production in the target fragmentation region in deep-inelastic $\mu N$ scattering.

Complementary nonperturbative phenomenon to polarized parton distribution in the polarized nucleon is the polarization transfer in the quark fragmentation process. I will present the results of our calculations [6, 7] for different phenomenological spin transfer mechanisms for the $\Lambda$ and $\Lambda$ longitudinal polarization in various lepton induced processes.

The leading twist unpolarized ($D^\Lambda_q(z)$) and polarized ($\Delta D^\Lambda_q(z)$) quark fragmentation functions to a $\Lambda$ hyperon are defined as:

$$D^\Lambda_q(z) = D^+\Lambda_q(z) + D^-\Lambda_q(z)$$

$$\Delta D^\Lambda_q(z) = D^+\Lambda_q(z) - D^-\Lambda_q(z),$$

where $D^+\Lambda_q(z)$ ($D^-\Lambda_q(z)$) is the spin dependent quark fragmentation functions for the $\Lambda$ spin parallel (antiparallel) to that of the initial quark $q$, and $z$ is the quark energy fraction carried by the $\Lambda$ hyperon.

We parametrize the polarized quark fragmentation functions as

$$\Delta D^\Lambda_q(z) = C^\Lambda_q(z) \cdot D^\Lambda_q(z),$$

where $C^\Lambda_q(z)$ are the spin transfer coefficients.

Two different descriptions of the spin transfer mechanism in the quark fragmentation to a $\Lambda/\bar{\Lambda}$ hyperon are considered. The first one is based on the non-relativistic quark model SU(6) wave functions, where the $\Lambda$ spin is carried only by its constituent $s$ quark. Therefore, the polarization of directly produced $\Lambda$'s is determined by that of the $s$ quark only, while $\Lambda$'s coming from decays of heavier hyperons inherit a fraction of the parent’s polarization, which might originate also from other quark flavors (namely $u$ and $d$). In this scheme the spin transfer is discussed in terms of constituent quarks. Table 2 shows the spin transfer coefficients $C^\Lambda_q$ for this case [8, 9]. A particular case is given by a simpler assumption that the $\Lambda$ hyperon gets its polarization from $s$ quarks only. In the following we will refer to the former description as BGH (for Bigi, Gustafson, and Håkkinen) and the latter as NQM (for naïve quark model).

The second approach is based on the $g_1^s$ sum rule for the first moment of the polarized quark distribution functions in a polarized $\Lambda$ hyperon, which was derived by Burkardt.
and Jaffe [10] in the same fashion as for the proton one ($g_1^p$). We assume that the spin transfer from a polarized quark $q$ to a $\Lambda$ is proportional to the $\Lambda$ spin carried by that flavor, i.e. to $g_1^\Lambda$. Table 3 contains the spin transfer coefficients $C_i^\Lambda$, which were evaluated using the experimental values for $g_1^p$. Two cases are considered [11]: in the first one only valence quarks are polarized; in the second case also sea quarks and antiquarks contribute to the $\Lambda$ spin. In the following we will refer to the first one as $BJ-I$ and the second one as $BJ-II$.

In the $g_1^\Lambda$ sum rule scheme a negative spin transfer from $u$ and $d$ quarks to a $\Lambda$ hyperon is predicted. This effect can be understood qualitatively even if the spin of the $\Lambda$ is determined by its constituent $s$ quark only: in some cases the fragmenting $u$ or $d$ quark will become a sea quark of the constituent $s$ quark, and the spin of the constituent $s$ quark will be anti-correlated to the spin of the fragmenting quark [3, 2]. Another possibility occurs when the $\Lambda$ is produced as a second rank particle in the fragmentation of a $u$ or $d$ quark. If the first rank particle was a pseudoscalar strange meson, then the spin of the $\bar{s}$ antiquark has to be opposite to that of the $u$ ($d$) quark, and since the $s\bar{s}$ pair created from the vacuum in the string breaking is assumed to be in a $^3P_0$ state, the $s$ quark is also oppositely polarized to the $u$ or $d$ quark. This last mechanism of the spin transfer can be checked by measuring the $\Lambda$ polarization for a sample of events containing fast $K$ mesons.

For charged lepton DIS the fragmenting quark longitudinal polarization is given by the simple parton model expression [7, 2]

$$P^q(x, y) = \frac{P_B D(y)q(x) + P_T \Delta q(x)}{q(x) + P_B D(y)P_T \Delta q(x)}.$$  \(8\)

For neutrino scattering the flavor changing charged current weak interaction selects left-handed quarks (right-handed antiquarks), giving 100\% polarized fragmenting quarks. The Standard Model predicts a high degree of longitudinal polarizations for quarks and antiquarks produced in $Z^0$ decays: $P_u = P_c = -0.91$, $P_d = P_t = -0.67$.

The results [8] for longitudinal $\Lambda/\bar{\Lambda}$ polarization in different processes are presented in the Figs. 4, 5 and 6. As one can see from the Fig. 4 the existing data [12] does not allow to distinguish between $BGH$ and $BJ$ mechanisms for the spin transfer. But, as one can see from Figs. 5 and 6 in the current fragmentation region of deep inelastic scattering

Table 2: Spin transfer coefficients according to non-relativistic SU(6) quark model.

| $\Lambda$’s parent | $C_u^\Lambda$ | $C_d^\Lambda$ | $C_s^\Lambda$ | $C_{\bar{q}}^\Lambda$ |
|--------------------|---------------|---------------|---------------|------------------|
| Quark              | 0             | 0             | +1            | 0                |
| $\Sigma^0$         | $-2/9$        | $-2/9$        | $+1/9$        | 0                |
| $\Sigma(1385)$     | $+5/9$        | $+5/9$        | $+5/9$        | 0                |
| $\Xi$              | $-0.3$        | $-0.3$        | +0.6          | 0                |

Table 3: Spin transfer coefficients according to the Burkardt-Jaffe $g_1^\Lambda$ sum rule.

|        | $C_u^\Lambda$ | $C_d^\Lambda$ | $C_s^\Lambda$ | $C_{\bar{q}}^\Lambda$ |
|--------|---------------|---------------|---------------|------------------|
| $BJ-I$ | $-0.20$       | $-0.20$       | +0.60         | 0.0              |
| $BJ-II$| $-0.14$       | $-0.14$       | +0.66         | $0.06$           |
Figure 4: a) $\Lambda/\bar{\Lambda}$ polarization at the $Z^0$ pole for different mechanisms of spin transfer: solid line - NQM, dashed - BGH, dotted - BJ-I, and dot-dashed - BJ-II. The experimental data (full squares) are from [12]. b) comparison between predictions using the BGH model for the $\Lambda$ polarization in our analysis (solid line) and the analysis of [12] assuming that only $s$ quarks contribute to $\Lambda$ polarization (dashed), and additionally that only first rank $\Lambda$’s inherit a fraction of the fragmenting quark polarization (dotted).

Figure 5: $\Lambda$ and $\bar{\Lambda}$ longitudinal polarization in the current fragmentation region for DIS of polarized $\mu^+$’s on an unpolarized target for different mechanisms of spin transfer: solid line - NQM, dashed - BGH, dotted - BJ-I, and dot-dashed - BJ-II.

The predicted $\Lambda/\bar{\Lambda}$ polarizations are rather different for the two mechanisms. Our studies have shown that the $\Lambda/\bar{\Lambda}$ polarization in the current fragmentation region of polarized electro-production is less sensitive to the target polarization (in general) and especially to $\Delta s$.

The new accurate data which are soon expected from NOMAD [13], HERMES [14] and COMPASS [7] experiments will provide possibility for detailed study of these interesting phenomena.
Figure 6: Λ/Λ polarization in the current fragmentation region in ν–DIS (upper plots) and ρ–DIS (lower plots): solid line - NQM, dashed - BGH, dotted - BJ-I, and dot-dashed - BJ-II.

References

[1] S. Willocq et al, (WA59 Collaboration), Z. Phys. C 53 (1992) 207.
[2] J. Ellis, D. Kharzeev, and A. Kotzinian, Z. Phys. C 69 467 (1996).
[3] J. Ellis, M.Karliner, D.E. Kharzeev, and M.G. Sapochnikov, Phys. Lett. B 353 319 (1995); M. Alberg, J. Ellis, and D.E. Kharzeev, Phys. Lett. B 355 113 (1995);
[4] W. Melnitchouk and A.W. Thomas, Z. Phys. A 353 311 (1996).
[5] S.J. Brodsky and B-Q. Ma, Phys.Lett. B 381 317 (1996).
[6] A. Kotzinian, A. Bravar and D. von Harrach, hep-ph/9701384, to be published in Z. Phys. C.
[7] The COMPASS Coll., CERN/SPSLC 96-14, SPSC/P297, March 1, 1996; see also HMC Letter of Intent, CERN/SPSLC 95-27, SPSC/I204, March 1995.
[8] I.I. Bigi, Nuovo. Cim. 41A, 43 (1977); I.I. Bigi, ibid 581.
[9] G. Gustafson and J. Hämäkinen, Phys. Lett. B 303, 350 (1993).
[10] M. Burkardt and R.L. Jaffe, Phys. Rev. Lett. 70, 2537 (1993).
[11] R.L. Jaffe, Phys. Rev. D 54, R6581 (1996).
[12] The ALEPH Coll., D. Buskulic et al., Phys. Lett. B 374, 319 (1996).
[13] The NOMAD Coll., CERN/SPSLC 91-121, SPSC/P261, 1991.
[14] The HERMES Coll., K. Coulter et al., DESY-PRC 90/01, 1990; M. Düren, DESY - HERMES 95-02 (1995).