THE PROTON SPIN PUZZLE AND 
Λ POLARIZATION IN DEEP–INELASTIC SCATTERING

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Abstract

We point out that measurements of longitudinal Λ polarization in the target fragmentation region of deep–inelastic $\nu N$ and $\mu N$ or $e N$ scattering may test dynamical mechanisms invoked to explain the proton spin puzzle. A previously-proposed model for polarized $\bar{s}s$ pairs in the proton wave function reproduces successfully the negative Λ polarization found in the WA59 $\bar{\nu} N$ experiment, and makes predictions that could be tested in future $\mu N$ and $e N$ experiments.
1 Introduction

Polarization measurements provide sensitive tests of models of strong–interaction dynamics, and have produced a number of surprises. The largest amount of discussion has been stimulated by measurements of polarized deep–inelastic lepton–nucleon scattering structure functions, which indicate that the angular momentum of the proton is not distributed among its parton constituents in the way expected in the naïve quark models. This discussion has been facilitated by the relatively well–understood theoretical framework of perturbative QCD, the operator product expansion and local operator matrix elements. Other puzzling polarization measurements, such as those of helicity–amplitude effects in \( pp \) elastic scattering or of \( \Lambda \) polarization in hadron–hadron and deep–inelastic scattering, have suffered from the lack of such a clear basis for conceptual analysis. Some modelling of nonperturbative QCD is essential for the interpretation of these experiments, as well as for understanding the local operator matrix elements determined by deep–inelastic structure–function measurements.

Broadly speaking, one can distinguish two principal trends in the interpretation of these deep–inelastic measurements. One notes that the measured values of axial current matrix elements \( \Delta q \cdot 2s_\mu = \langle p|q\gamma_\mu\gamma_5q|p\rangle \), in particular the smallness of the singlet axial current matrix element \( \langle p|A_0^0|p\rangle = \Delta \Sigma \cdot 2s_\mu : \Delta \Sigma = \Delta u + \Delta d + \Delta s \), are closer to the values expected in chiral soliton models in the twin limits of massless quarks and a large number of colours \( N_c \), and interprets the data in terms of the topology of the flavour \( SU(3) \) group as reflected in such chiral soliton models \[1\]. The other trend assigns responsibility for the smallness of \( \langle p|A_\mu^0|p\rangle \) to the \( U(1) \) axial–current anomaly, which may play either perturbatively, via a gluonic correction to the polarized quark–parton distributions in the proton wave function: \( \Delta q \to \Delta q - (\alpha_s/2\pi) \Delta G \), or nonperturbatively via a dynamical suppression of the \( U(1) \) topological susceptibility \[2\].

The perturbative approach to suppression of the axial \( U(1) \) matrix element invokes a large polarized gluon distribution \( \Delta G \) which is absent from the chiral soliton approach. These models are, therefore, easy to distinguish in principle, and various proposals have been made for measuring the gluon polarization via hard processes in deep–inelastic scattering and elsewhere. Some experimental information is starting to become available, but no test discriminating clearly between these models has yet been made. At our present level of understanding, any such test which goes beyond the perturbatively–calculable hard–scattering framework necessarily involves additional nonperturbative assumptions or inputs, for example in modelling the polarized proton wave function.

One such model has recently been proposed \[3, 4\], in which a valence quark core with (essentially) the naïve quark model spin content may be accompanied by a spin–triplet \( \bar{s}s \) 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: \( \langle 0|\bar{u}u, d\bar{d}, \bar{s}s|0\rangle \neq 0 \). This model has been shown to reproduce qualitatively experimental features of \( \phi \) production in \( \bar{p}N \) annihilation and used to make further predictions for \( \phi \) and \( f_2^\prime \) production \[3\], and for depolarization in \( pp \to \Lambda\Lambda \) \[4\]. In the latter case, our model predictions differ from those that could be expected in models with a large polarized gluon distribution in the proton wave function.
In this paper we first point out that our polarized $\bar{s}s$ model \cite{3, 4} provides a natural interpretation of data on longitudinal $\Lambda$ polarization in the target fragmentation region in deep–inelastic $\nu N$ collisions. In our model, the polarized $W$ emitted by the $\nu$ selects a polarized quark from the target nucleon wave function. Any $\bar{s}s$ pair in the remnant wave function would have the opposite polarization, which can be transferred to final–state $\Lambda$ polarization. This is indeed observed to be negative, and the polarization transfer efficiency seems to be about 70%. A polarized–gluon model appears likely to yield the opposite sign of $\Lambda$ polarization in the target fragmentation region.

We then use our model to make predictions for $\Lambda$ polarization in deep–inelastic $\mu N$ or $e N$ collisions. In this case, the polarized $\mu$ or $e$ beam emits a virtual photon with non–zero longitudinal polarization, which in turn selects preferentially one polarization state of the struck quark. In our model, the opposite polarization of a remnant $\bar{s}s$ pair can again be transferred to final–state $\Lambda$ polarization, with the efficiency extracted from $\nu N$ collisions. We present detailed predictions for $\Lambda$ polarization in the target fragmentation region for both polarized and unpolarized targets, and also make predictions for correlations between $\Lambda$ and $\bar{\Lambda}$ polarization measurements in the current and target fragmentation regions.

The layout of this paper is as follows. Our model for polarized $q$ distributions in the nucleon wave function is reviewed in Section 2. Our interpretation of the $\nu N$ data is presented in Section 3, accompanied by quantitative results for different kinematic regions obtained using the LEPTO Monte Carlo program. This program is then used in Section 4 to make quantitative predictions for the target and current fragmentation regions in $\mu N$ and $e N$ scattering, and correlation measurements are discussed in Section 5. Finally, in Section 6 we draw some conclusions and compare our predictions with what might be expected qualitatively in a polarized–gluon model.

2 Model for polarized quark distributions

Results from the deep–inelastic scattering experiments \cite{3} clearly indicate that the contribution of light quarks to the spin of the proton is small: $\Delta \Sigma = \Delta u + \Delta d + \Delta s \ll 1$. This comes as a surprise from the point of view of the naïve constituent quark model, which would suggest $\Delta \Sigma \approx \Delta u + \Delta d \approx 1$, and $\Delta s = 0$. The experimental data also allow to extract the separate contributions of $u, d$ and $s$ quarks \cite{3}:

$$\Delta u = 0.83 \pm 0.03, \quad \Delta d = -0.43 \pm 0.03, \quad \Delta s = -0.10 \pm 0.03.$$  \hspace{1cm} (1)

Strange quarks therefore appear to have a net polarization opposite to the proton spin. Though the matrix elements $\Delta u$ and $\Delta d$ involve both valence and sea quarks, the small value of $\Delta \Sigma$ suggests that the light quark sea is also negatively polarized, so as to compensate to large extent the spin carried by the valence quarks.

The origin of this negative sea polarization is likely nonperturbative and still has to be understood. One model motivated by chiral dynamics has recently been proposed \cite{3, 4}. It is based on two major observations. First, the fact that the masses of Goldstone bosons of spontaneously broken $SU(3)_L \times SU(3)_R$ chiral symmetry – pions and kaons – are small at the typical hadronic scale can be attributed to the existence of effective
strong attraction between quarks and antiquarks in the pseudoscalar $J^{PC} = 0^{-+}$ channel. Secondly, from phenomenological analyses of the quark condensates in the framework of the QCD sum rules \cite{7}, \cite{8} it is known that the density of quark-antiquark pairs in nonperturbative vacuum is quite high:

$$
\langle 0|\bar{u}u|0\rangle \simeq \langle 0|\bar{d}d|0\rangle \simeq (250\text{MeV})^3, \quad \langle 0|\bar{s}s|0\rangle \simeq (0.8 \pm 0.1)\langle 0|\bar{q}q|0\rangle.
$$

(2)

It is worthwhile to note that Eq(2) indicates that the density of strange quarks in the vacuum is comparable to the density of $u$ and $d$ quarks.

Let us now consider, following \cite{4}, the basic $|uud\rangle$ proton state immersed in the QCD vacuum. The strong attraction in the spin-singlet pseudoscalar channel discussed above will induce correlations between valence quarks from the proton wave function and vacuum antiquarks with opposite spins. As a consequence of this, the spin of the antiquarks will be aligned opposite to the proton spin. Moreover, we note that in order to preserve the vacuum quantum numbers ($J^{PC} = 0^{++}$), quark-antiquark pairs must be in a relative spin-triplet, $L = 1^{2}P_{0}$ state. Therefore the spin of vacuum sea quarks must also be aligned opposite to the proton spin. The resulting wave function of the proton will therefore contain negatively polarized $\bar{q}q$ components, which will effectively decrease the fraction of the proton spin carried by quarks. The negative contribution to the spin will be compensated by a positive contribution from orbital angular momentum, so the total angular momentum sum rule of course will be satisfied. The proposed mechanism can be interpreted as an effective vacuum “screening” of the quark (and proton) spin in the nonperturbative vacuum with spontaneously broken chiral symmetry.

In view of (2), this mechanism should be applicable to $\bar{s}s$ components as well as $\bar{u}u$ and $\bar{d}d$. Therefore we expect that the proton wave function will contains a considerable admixture with an $\bar{s}s$ component:

$$
|p\rangle = v \sum_{X=0}^{\infty} |uudX\rangle + z \sum_{X=0}^{\infty} |uuds\bar{s}sX\rangle + \cdots,
$$

(3)

where $X$ denotes Fock space components not containing $\bar{s}s$ pairs, and the dots denote components with two or more $\bar{s}s$ pairs, which we assume to be negligible so that $|v|^2 + |z|^2 \simeq 1$. The simplest wave function of the $\bar{s}s-$ containing component, consistent with the dynamical chirality and spin arguments discussed above, corresponds to a spin-triplet, polarized $S_z = -1$ $\bar{s}s$ pair with angular momentum $L_z = +1$ coupled to the “usual” $S_z = 1/2$ $|uud\rangle$ valence state.

Within this general framework, it is possible to imagine that each constituent quark, in a naive quark model for the proton wave function, contains a valence $u$ or $d$ quark with the same polarization as the parent constituent quark, and its own individual sea of $\bar{q}q$ pairs with the above-mentioned spin correlations. In a deep-inelastic scattering event in which one of the valence quarks is struck, it might be a good approximation to consider its parent constituent quark as being the only one dissociated, with the other constituent quarks left essentially intact as spectators. In this refinement of the model of \cite{4}, the polarization of the remnant $\bar{s}s$ pair would be 100% anticorrelated with that of the struck valence quark (or its parent constituent quark).
The “experimental” value (1) suggests that
\[ |z|^2 \simeq -\Delta s \simeq 0.10, \tag{4} \]
which is consistent with the limits derived from the phenomenology of \( \bar{s}s \) production in \( \bar{p}N \) annihilation [3]:
\[ 0.01 \leq |z|^2 \leq 0.19. \tag{5} \]
This polarized intrinsic strangeness model has been shown to reproduce qualitatively the channel–dependent, non–universal excess of \( \phi \) production in \( \bar{p}N \) annihilation at rest observed recently at LEAR [10]. Within this approach, a large apparent violation of the OZI rule is interpreted in terms of “rearrangement” and “shake–out” of an intrinsic \( \bar{s}s \) component of the nucleon wave function.

The self–analyzing properties of \( \Lambda \) (\( \bar{\Lambda} \)) make this particle especially interesting for spin physics. This hyperon can be used as a \( s \) quark polarimeter since the polarization of \( \Lambda \) is defined by polarization of its \( s \) quark. The production of \( \Lambda\Lambda \) pairs in \( \bar{p}p \) annihilation in our model is viewed [3] as the dissociation of a spin-triplet \( \bar{s}s \) pair from the initial proton or antiproton into a \( \Lambda\Lambda \) state. Since the spin of the \( \Lambda \) is carried by the spin of the strange quark, this (spin–correlation–conserving) dissociation leads to a spin–triplet final state for the two hyperons. This is indeed consistent with the experimental observation [9] that the spin–singlet fraction in the \( \bar{\Lambda}\Lambda \) final state is equal to zero within statistical errors. Since the initial \( \bar{s}s \) pair carries a polarization opposite to the (anti)proton spin, the model also predicts that the spin of the final \( S = 1 \) \( \bar{\Lambda}\Lambda \) pair is polarized in the direction opposite to the spin of initial spin-triplet \( \bar{p}p \) state, and therefore the depolarization \( D_{nn} \) is negative. This prediction can be tested experimentally in the near future [11]. It is, however, important to test the polarized intrinsic strangeness model in the same kinematical conditions in which the contribution of the strange quarks to the spin of the proton \( \Delta s \) is measured, i.e., in deep–inelastic scattering. In the next Sections we will discuss the consequences of this model for the polarization of the \( \Lambda \)'s produced in deep–inelastic scattering.

3 Polarization of \( \Lambda \)'s in the Target Fragmentation Region in Deep-Inelastic \( \bar{\nu} \) Scattering

Measurements of \( \Lambda \) polarization have been made in the target fragmentation region (\( x_F < 0 \)) in \( \nu \) and \( \bar{\nu} \) deep-inelastic scattering experiments [12]–[15]. Non-trivial negative longitudinal polarization, measured with respect to the direction of the momentum transfer from the beam, has been observed in two experiments [12]–[13], whereas the data on transverse \( \Lambda \) polarization are quite contradictory. The longitudinal-polarization data of the WA59 experiment [12] have the best statistical accuracy, and in this Section we present an interpretation of these data using the simple model of the polarized nucleon wave function described in Section 2.

The essence of our argument is that the right-handed polarization of the \( \bar{\nu} \) beam is transferred to the hadrons via polarized \( W^- \)-exchange, which selects preferentially one longitudinal polarization state of the nucleon target, which is reflected in nontrivial
longitudinal polarization of Λ’s produced in the target fragmentation region. Specifically, in most interactions the ¯ν-induced W removes a positively-polarized u quark from the nucleon target, as seen in Fig. 1. The naïve model of Section 2 then predicts that any s quark in the target fragment should have negative longitudinal polarization, so that the longitudinal Λ polarization should also be negative, as observed.

Figure 1: Dominant diagram for Λ 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.

To be more quantitative, we denote by $P_{s\pm q}$ ($P_{s\pm \bar{q}}$) the probability that the longitudinal projection of the remnant s quark spin is parallel/antiparallel to that of the struck quark $q$ (antiquark $\bar{q}$), and define the spin-correlation coefficient

$$c_{s q} = \frac{P_{s+q} - P_{s-q}}{P_{s+q} + P_{s-q}}.$$  \hspace{1cm} (6)

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

$$P_s = \frac{\sum_q c_{s q} N_q - \sum_{\bar{q}} c_{s \bar{q}} N_{\bar{q}}}{N_{tot}},$$  \hspace{1cm} (7)

where $N_q$ ($N_{\bar{q}}$) is the total number of events selected in which a quark (antiquark) is struck, and $N_{tot} = N_q + N_{\bar{q}}$ is the total number of events selected. The antiquarks contribute with a negative sign because their charged-current weak interactions are righthanded. The relative proportion of $q$ and $\bar{q}$ events depend in general on the range of the kinematic variables selected, leading to dependencies of $P_s$ on the kinematic variables, as we discuss in more detail below.

According to the simple polarization model discussed in the previous section, the polarization of the remnant s quark is 100% anticorrelated with that of the valence quark, and 100% correlated with that of struck sea $\bar{s}$ antiquark (see Fig. 2):
Figure 2: Diagram for Λ 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.

\[
\begin{align*}
  c_{u_{val}} &= c_{d_{val}} = -1, \\
  c_{s_{sea}} &= \delta_{\bar{s}\bar{q}}.
\end{align*}
\]

The correlation of the remnant $s$ quark polarization with that of any other struck sea quark depends whether they come from the same parent constituent quark. If yes, which might be the dominant case, we would expect

\[
c_{s_{sea}} = 1.
\]

If no, however, the correlation would be reduced. The predictions we present later are insensitive to the value of $c_{s_{sea}}$ in the region of Bjorken $x > 0.15$, and also for lower $x$ in $\bar{\nu} N$ scattering. For definiteness we use (9) in the following.

According to the simple quark model of the polarized Λ wave function, the polarization of a directly-produced Λ is the same as that of the remnant $s$ quark. However, final-state Λ’s may also be produced indirectly via the decays of heavier hyperon resonances, which tends to dilute the Λ polarization by a factor we denote by $D_F$. Thus the final-state longitudinal Λ polarization is

\[
P_\Lambda = D_FP_s,
\]

where $P_s$ is given by equation (7). The fraction of Λ’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 latest version of the Lund Monte Carlo program LEPTO6.2 [16], with default values of parameters, to obtain numerical results. This program provides a good description of the existing data on unpolarized semi-inclusive hadron production in deep-inelastic scattering. We implement into it the spin correlations following from our model (see (5), (6)). We have generated a sample of deep-inelastic events with the $\bar{\nu}$ energy set equal to the average value in the WA59 experiment, using its target composition and kinematical cuts, and then selected events with Λ’s produced in the target fragmentation.
region. We present in 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 expected remnant $s$ quark polarization is smaller in the low-$x$ region ($x < 0.2$) where the relative weight of events with struck sea $u$, $\bar{d}$ and $c$ quarks is higher than in the valence-quark region ($x > 0.2$). Comparing the values of $P_s$ and $P_\Lambda$ in this valence region, we conclude that the polarization of $\bar{s}s$ pair must indeed be highly correlated with that of the valence quark: $c_s u_{val} \approx 1$ as we have assumed.

The lower value of $P_\Lambda$ in the sea region ($X < 0.2$) may be due in part to the larger relative weight of struck sea-quark events, and in part to a larger fraction of $\Lambda$'s being produced indirectly via the decays of heavier hyperons in this $x$ range, where the invariant hadronic mass is larger.

We are gratified that our naïve model describes correctly the sign, order of magnitude and $x$ dependence of longitudinal $\Lambda$–polarization in deep-inelastic $\bar{\nu} N$ collisions.

It is interesting to contrast the above predictions of the polarized $s\bar{s}$ sea model with what might be expected if the EMC/SMC effect is essentially due to positively-polarized gluons [2]. In such a model, we would naïvely expect the depolarization in $p\bar{p} \to \Lambda \bar{\Lambda}$ and the polarization of $\Lambda$'s from target fragmentation the WA59 experiment (see Fig. 3) to be positive, i.e., opposite in sign to the polarized $s\bar{s}$ sea model and to what was in fact observed in the WA59 experiment. Detailed calculations in the polarized gluon model lie, however, beyond the scope of this note.

4 Polarization of $\Lambda$’s in the Target Fragmentation Region in Deep-Inelastic $\mu$ or $e$ Scattering

Encouraged by the successful interpretation of WA59 data in the previous Section, in this section 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 on both unpolarized and polarized nucleon targets, as in the experiment proposed at CERN [17] and in polarized $eP$ scattering, as in the HERMES experiment [18].
Our argument for $\mu N$ scattering based on the fact that muon beams are naturally longitudinally polarized, because the beam particles are produced by charged-current weak decays. The degree of longitudinal polarization, $P_B$, depends on the beam characteristics. Since scattering via the electromagnetic interaction has different cross sections for different quark longitudinal polarization states, the struck quark (or antiquark) in the target has non-zero net longitudinal polarization, and the model of the Section 2 then suggests a \textit{negatively-correlated} remnant $s$ quark polarization which may be transferred to $\Lambda$’s produced in the target fragmentation region. The observation by WA59 collaboration of large negative longitudinal $\Lambda$ polarization in the target fragmentation region of $\bar{\nu} N$ scattering suggests that the polarization transfer mechanism does not involve strong dilution of the remnant $s$ quark polarization.

We consider electromagnetic lepton-quark scattering in its center-of-mass system. with $z$ axis along lepton momentum. Depending on the relative sign of the lepton and quark longitudinal spin projections, this process may take place in the $s$-wave or in the $p$-wave. In the $s$-wave case, the scattering probability is independent of $y$, whereas in the $p$-wave case is proportional to $(1 - y)^2$, where $y$ is usual deep-inelastic energy loss variable. The probability that the lepton has positive/negative longitudinal spin projection is

$$w^{l}_\pm = \frac{1}{2}(1 \pm P_B).$$

(11)

Analogously, the probability to find a quark (antiquark) with nucleon-momentum fraction $x$ and positive/negative longitudinal spin projection is

$$w^{q}_\pm(x) = \frac{1}{2}[q(x) \pm P_T \Delta q(x)],$$

(12)

where $P_T$ is the target polarization and $q(x)$ and $\Delta q(x)$ are unpolarized and polarized quark distribution functions, respectively. The lepton-quark interaction probability depends as follows on the signs of the longitudinal spin projections $w^{l}_i k(i, k = +, -)$:
\begin{align}
    w_{++}^l &= e_q^2 w_{++}^q(x)(1-y)^2,
    w_{+-}^l &= e_q^2 w_{+-}^q(x),
    w_{-+}^l &= e_q^2 w_{-+}^q(x),
    w_{--}^l &= e_q^2 w_{--}^q(x)(1-y)^2,
\end{align}

(13)

where \( e_q \) is the quark charge.

For the struck quark longitudinal polarization \( P_q \), we get \(^4\)

\[
P_q = \frac{\sum_i (w_{i+}^q - w_{i-}^q)}{\sum_i (w_{i+}^q + w_{i-}^q)} = \frac{P_T\Delta q(x) - P_B D(y)q(x)}{q(x) - P_B P_T D(y)\Delta q(x)},
\]

(14)

where

\[
D(y) = \frac{1 - (1-y)^2}{1 + (1-y)^2}
\]

(15)

which is commonly referred as longitudinal depolarization of virtual photon with respect to parent lepton. Using the spin correlation coefficient introduced in Section 3, it is easy to find the following expression for the polarization of the remnant \( s \) quark

\[
P_{s,rem} = \frac{\sum_{i,q} [w_{i+}^q - w_{i-}^q] c_{s,q}}{\sum_{i,q} [w_{i+}^q + w_{i-}^q]} = \frac{\sum_q e_q^2 [P_T\Delta q(x) - P_B D(y)q(x)] c_{s,q}}{\sum_q e_q^2 q(x) - P_B P_T D(y)\Delta q(x)},
\]

(16)

where the summation over \( q \) here means summation over both quarks and antiquarks.

We see in formulae (14) and (16) that there are two potential sources of longitudinal polarization of the struck quark and remnant \( s \) quark: target polarization, and polarization induced by interaction with the polarized beam. Note the nonlinear dependence of expressions (14) and (16) on beam and target polarization.

We have again used LEPTO6.2 to obtain numerical results, by generating deep-inelastic scattering events with \( \Lambda \) production, using the beam energy and kinematical cuts corresponding to those of the SMC experiment. The remnant \( s \) quark polarization was calculated according to formula (16) with polarized quark distributions from the paper by Brodsky, Burkardt and Schmidt \(^{[20]}\).

In the sea-quark region, the remnant \( s \) quark polarization is much smaller than in deep-inelastic \( \bar{\nu} N \) scattering. In the \( \bar{\nu} \) case, events with a final–state \( \Lambda \) produced in the target fragmentation region due to scattering on an \( s \) antiquark play an important role, and their contribution to \( P_s \) has the same sign as that from valence \( u \) quarks (see Fig. 1 and Fig. 2). In the \( \mu \) case, the relative weights of other sea quarks are higher, and contributions from valence \( u \) quarks and \( \bar{s} \) antiquarks have opposite signs (see Fig. 4 and Fig. 5). Here, we present predictions only for the valence-quark region: \( x > 0.15 \): for the reason mentioned above, the calculations performed in the region \( x < 0.15 \) would yield

\(^4\)A more general expression for the struck quark polarization, including effects of the intrinsic transverse momentum of quarks can be found, for example, in \(^{[19]}\).
smaller values of $\Lambda$ polarization, due to a weaker spin correlation between the struck light sea quark and the remnant $s$ quark, and would depend more on details of our model. We also impose the $y$-cut $y > 0.5$, so as to select events in which the polarization transfer from the beam is big (see eqs. (14) and (15)).

Figure 4: Dominant diagram for $\Lambda$ production in deep-inelastic $\mu N$ scattering on a valence $u$ quark.

Figure 5: Diagram for $\Lambda$ production in a deep-inelastic event due to $\mu$ interaction with an $\bar{s}$ antiquark from sea.

For the new experiment proposed at CERN [17], ammonia ($\text{NH}_3$) is chosen as the target material. We can treat this target approximately as an incoherent sum of seven unpolarized neutrons, seven unpolarized protons and three polarized protons (with polarization $P_T$). The results of our calculations for a $\mu$ beam with the natural longitudinal polarization $P_\mu = -0.8$ are shown in Fig. 6, together with the cases $P_\mu = 0$ and 0.8. The spin correlation coefficients are taken from (3).

For deep-inelastic scattering on an ammonia target, most of the remnant $s$ quark polarization $P_s$ is induced by polarization transfer from the lepton, and the difference
Figure 6: 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 as in the proposed CERN experiment [17] and the following cuts were applied: $-0.3 < x_F < 0$, $x > 0.15$, $0.5 < y < 0.9$.

between $P_s$ for targets polarized with opposite signs is smaller than in the proton target case.

The produced $\Lambda$ polarization is given by equation (10). We concluded from our analysis of the WA59 data that in the valence-quark region the fragmentation dilution factor $D_F \gtrsim 0.7$. Therefore, we expect large polarization effects also for $\Lambda$ production in the target fragmentation region in deep-inelastic $\mu N$ scattering.

Calculations of the remnant s quark polarization for $e P$ scattering, with $\Lambda$ produced in the target fragmentation region and a beam energy $E_e = 27.5$ GeV as in the HERMES experiment [18], are shown in Fig. 7. The differences between Figs. 7 and 6 a are mainly due to the different beam polarizations assumed. Energy-dependent scaling violation effects are relatively unimportant.

In the polarized-gluon model (see Fig. 8), we would naïvely expect the polarization of $\Lambda$’s to be opposite in sign from the polarized $\bar{s}s$ sea model, though a detailed exploration goes beyond the scope of this paper.
Figure 7: Polarization of remnant $s$ quark for deep-inelastic polarized $eP$ scattering, as a function of the target polarization $P_T$ for different values of the beam polarization. A beam energy $E_e = 27.5$ GeV as in the HERMES experiment [18] was assumed, and the following cuts were applied: $x_f < 0$, $x > 0.15$ and $0.5 < y < 0.85$.

5 Λ ¯Λ Polarization Correlation Measurements

It is interesting to consider also polarization effects in the associated production of Λ and ¯Λ, for which we restrict our attention here to the unpolarized ammonia target case.

We first consider the case when a Λ is produced in the target fragmentation region and a ¯Λ in the current fragmentation region in $\mu N$ scattering. In Table 4 we show the predicted Λ and ¯Λ polarizations obtained using LEPTO6.2 Monte Carlo program with polarization effects implemented as described previously. Calculations are made assuming that there is no dilution ($D_F = 1$) in the polarization transfers from the $s$ quark to the Λ and from the ¯$s$ antiquark to the ¯Λ. We make the kinematical cuts $y > 0.5$, $x_\Lambda^F < -x_0^F$ and $x_{\bar{\Lambda}}^F > x_0^F$ for various values of $x_0^F$.

| $x_0^F$ | $P_\Lambda$ | $P_{\bar{\Lambda}}$ |
|---------|-------------|---------------------|
| 0.1     | -0.07      | -0.17               |
| 0.2     | 0.06       | -0.27               |
| 0.3     | 0.23       | -0.40               |

Table 2: Polarization of associatively-produced Λ and ¯Λ with $y > 0.5$ and $x_\Lambda^F < -x_0^F$ and $x_{\bar{\Lambda}}^F > x_0^F$, for various choices of $x_0^F$.

As can be seen in Table 2, the maximal polarization values are found when the Λ and ¯Λ
are produced at high $x_F^0$. In this case of large rapidity separation, the dominant mechanism of associated production is shown in the diagram of Fig. 5, with the $\Lambda$ produced from the $\bar{s}$ antiquark fragmentation. In the case of an unpolarized target, the $\bar{s}s$ polarization state is determined by the spin transfer from the polarized $\mu$. For this reason, the order of magnitude and the signs of the polarizations of the $\Lambda$ and $\bar{\Lambda}$ produced with large rapidity separations have to be the same also in the polarized-gluon model.

Results for the case when both the $\Lambda$ and the $\bar{\Lambda}$ are produced in the target fragmentation region are shown in Table 3. In this case, the dominant diagram for $\Lambda - \bar{\Lambda}$ pair production is that of Fig. 4, where the $\bar{\Lambda}$ produced in the target fragmentation region inherits the polarization of the $\bar{s}$ quark. At all values of $x_F^0$ the dominant mechanism of associated $\Lambda - \bar{\Lambda}$ production is scattering on the valence $u$ quark. For this reason, in contrast to the previous case, in the polarized-gluon model we would expect the opposite sign for the $\Lambda$ and $\bar{\Lambda}$ polarizations.

### 6 Conclusions

We have discussed in this paper ways in which measurements of $\Lambda$ polarization in deep-inelastic final states may cast light on the proton spin puzzle. Our suggestion is that $\Lambda$’s in the target fragmentation region are likely to have longitudinal polarization inherited...
from that of remnant $s$ quarks in the struck nucleon. We use a simple model \cite{3,4} of the nucleon spin structure in which the $s$ and $\bar{s}$ polarizations are anticorrelated with that of any valence quark struck by the polarized lepton probe. Our model reproduces successfully the sign, magnitude and $x$ dependence of the longitudinal $\Lambda$ polarization measured in the WA59 deep-inelastic $\bar{\nu}N$ experiment in the target fragmentation region. We have also applied the model to make predictions for the longitudinal polarization of $\Lambda$’s in the target fragmentation region in deep-inelastic $\mu N$ scattering off either a polarized or an unpolarized target, which are shown in Fig. 6, and polarized deep-inelastic $eP$ scattering, as shown in Fig. 7.

A preliminary Monte-Carlo study shows \cite{17} that the proposed new CERN experiment could collect in one year of data taking about $3 \cdot 10^5$ events with $\Lambda$’s produced in the target fragmentation region ($-0.3 < x_F < 0$). After kinematical cuts $x > 0.15$ and $y > 0.5$, several thousand deep-inelastic events will be retained, which is higher by an order of magnitude than in the WA59 experiment. Taking into account the predicted degree of polarization, it seems that the proposed new experiment at CERN \cite{17} is capable of performing measurements of $\Lambda$ polarization with sufficient accuracy to test our model.

We emphasize that our model for the nucleon spin structure is not rigorous, and represents an extrapolation of our present knowledge of polarized structure functions \cite{3}. It relies on the interpretation of these data as due to polarized $s\bar{s}$ pairs in nucleon \cite{4}, rather than polarized gluons \cite{2}. The development of this latter model to make predictions for $\Lambda$ polarization in deep-inelastic scattering lies beyond the scope of this paper. However, as we have indicated in previous Sections, it seems to us likely that a plausible extrapolation of the polarized-gluon model would predict the opposite sign for longitudinal $\Lambda$ polarization in the target fragmentation region in deep-inelastic $\bar{\nu}N$ and $\mu N$ or $eN$ scattering. It seems to us that it would be interesting for advocates of the polarized-gluon interpretation of the polarized structure-function data to examine this question. As we discussed in the previous paragraph, the statistics for $\Lambda$ production in the proposed new experiment at CERN \cite{17} are likely to be sufficient to determine the sign of the $\Lambda$ longitudinal polarization, and may therefore be able to cast some light on the proton spin puzzle.

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