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Transverse Λ^0 polarization in inclusive quasi-real photoproduction at the current fragmentation

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Abstract. It is shown that the recent HERMES data on the transverse Λ^0 polarization in the inclusive quasi-real photoproduction at $x_{\mathrm{F}} > 0$ can be accommodated by the strange quark scattering model. Relations with the quark recombination approach are discussed.

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1 Introduction

The polarization of Λ^0 hyperons has been under scrutiny almost since the very moment of its discovery. Investigations of the phenomenon received especially great impetus in 1976 due to the striking experimental results obtained at FERMILAB, where the hyperons produced in pN collisions at 300 GeV proton beam energy were highly polarized [1]. The polarization was transverse and negative, directed opposite to the unit vector $\mathbf{n} \propto [\mathbf{p}_{\mathrm{b}} \times \mathbf{p}_{\Lambda}]$, where $\mathbf{p}_{\mathrm{b}}$ and $\mathbf{p}_{\Lambda}$ are the beam and hyperon momenta, respectively.

Only this direction is allowed by the parity conservation in strong interactions provided that the incident particles are unpolarized (henceforth, under polarization we imply just the transverse one unless otherwise stated). The results turned out to be in disagreement with the predictions of perturbative QCD, no polarization had been expected to play any significant role in high energy processes as the helicity is conserved in the limit of massless quarks.

The polarization has also been observed in other hadron–hadron reactions at different kinematic regimes [2]. Its features qualitatively coincide in almost all the reactions, being insensitive, for instance, to the incident particle energy, exhibiting a roughly linear growth by magnitude with the transverse momentum p_{T} of the hyperon and being negative. The only known exception is the K^-p process, where the polarization sign has been found to be positive [3].

Certainly, many models have been proposed attempting to account for the results, see e.g. [4–16]; however, neither of them is able to describe the complete set of the available measurements.

The wave function of the Λ^0 facilitates theoretical studies allowing one to describe the phenomenon in a reasonable way. The exact SU(6) symmetry requires the spin–flavor part of the wave function to be combined of the ud diquark in a singlet spin state and the strange quark of spin 1/2, or formally $|\Lambda\rangle_{1/2} = |ud\rangle_0 |s\rangle_{1/2}$, where the subscriptions denote the spin states. Therefore, the total spin of Λ^0 is entirely given by the spin of its valence s quark. There is also an alternative way to look at the spin transfer in fragmentation; this has appeared after publication of the polarized deep inelastic lepton–nucleon scattering (DIS) data of the EMC Collaboration [17, 18]. It suggests that the spin carried by the valence quarks is only a part of the total nucleon spin, the rest being attributed, for example, to the orbital angular momenta of the valence quarks and to the nucleon sea (sea quarks, antiquarks and gluons). Which picture, SU(6) or DIS, is suitable for the description of the process still remains an important issue [19–24]. The Λ^0 hyperon can here provide a useful instrument for the study of the spin effects in the strong interactions.

We used the SU(6) approach throughout this paper. The choice was dictated by the wish to keep the quark scattering model as it is, encouraged by the SU(6) based calculations of the longitudinal Λ^0 polarization in e^+e^- annihilation at the Z^0 pole [25] and their successful experimental verification [26, 27].

According to the empirical rules proposed by DeGrand and Miettinen, the polarization sign depends on whether the s quark is accelerated (increases its energy) or decelerated (decreases its energy) in the Λ^0 formation process [5]. To illustrate, there are no valence s quarks in the initial state of the pp reaction, so that they come from the quark sea to form the final Λ^0. But the sea quarks predominantly populate small x-states (x is the Bjorken variable)

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and consequently increase their average energy coming in the valence content of Λ^0. Here the polarization is negative. On the contrary, the incident pseudoscalar kaons of the K^-p reaction already contain valence strange quarks mostly decelerated in the hadronization because the average energy of the created Λ^0 is less than that of the K^- beam. In this case the sign is positive. Similar ideas were implemented in flux-tube models with orbital angular momentum [4].

It was natural to wonder whether the polarization took place in Λ^0 electro- and/or photoproduction. Would one here observe the same features with hadron–hadron reactions? These questions have been investigated, for example, in experiments on high energy γN scattering performed at CERN [28] and SLAC [29] in the beginning of the eighties. However, their statistical accuracy is indecisive and would hardly enable one draw conclusions on the magnitude or on the sign of the polarization.

The transverse Λ^0 polarization has also been measured in unpolarized e^+e^- annihilations, for example, by the TASSO Collaboration at 14, 22 and 34 GeV center-of-mass (CMS) energies [30] and near the Z^0 pole by OPAL [27]. The polarization observed in both experiments is consistent with zero. Practically, this process can be a good place for deriving some important information on the hadronization phase. In particular, it can assist our understanding of to which extent final state interactions contribute to the transverse polarization [31].

In light of the scarce statistics for the Λ^0 photoproduction process, the HERMES experiments on the 27.6 GeV positron beam scattering off the nucleon target acquires a particular status, providing a good opportunity for observation of the polarization in electroproduction. The collaboration has measured nonzero positive transverse polarization, when most of the intermediate photons are quite close to the mass shell, i.e. $Q^2 = -(p_{ei} - p_{ef})^2 \approx 0\,\mathrm{GeV}^2$ [32], where p_{ei} and p_{ef} are the 4-momenta of the initial and scattered electrons, respectively (quasi-real photoproduction).

The experimental properties of the polarization at HERMES turned out to be very reminiscent of those in the K^-p reaction [3], which has been successfully described by a model assuming the polarization to appear mostly via strange quark scattering in a color field [6, 7].

Thus, there are indications that the mechanisms responsible for the phenomenon in the K^-p and ep may be similar, at least, within the covered kinematic region. These arguments inspired us to apply the model to the Λ^0 quasi-real photoproduction data obtained by HERMES.

Another goal of this paper is to qualitatively discuss some relations between the calculations presented herein and the quark recombination model (QRM) [14].

2 Quark scattering model for Λ^0

Electrons, when scattering off nuclei, have been known to be able to acquire polarization. Analytically, it can be found within QED by considering a process of Dirac point-like particle scattering off a static Coulomb potential provided next-to-leading order amplitudes are taken into account [33–35]. The corresponding formula reads

$$\mathbf{P} = \frac{2\alpha_{\mathrm{em}} m p}{E^2} \frac{\sin^3\theta/2 \ln(\sin\theta/2)}{[1 - p^2/E^2 \sin^2\theta/2]\cos\theta/2}\mathbf{n}\,, \tag{1}$$

where E, p, m and θ are the energy, magnitude of the momentum, mass and scattering angle of the electron, respectively, α_{em} is the fine structure constant, $\mathbf{n} \propto [\mathbf{p}_i \times \mathbf{p}_f]$, $\mathbf{p}_i$ and $\mathbf{p}_f$ are the vectors of the electron momenta in the initial (i) and final (f) states.

In [6], Szwed proposed to explain the Λ^0 polarization as polarization of its valence strange quark in scattering using (1), and the wave function of the Λ^0 favors such a consideration quite well. The idea is to perform the following interchanges in (1): electron $\leftrightarrow$ quark, $\alpha_{\mathrm{em}} \leftrightarrow C\alpha_{\mathrm{s}}$ (Coulomb potential $\leftrightarrow$ color field), where α_{s} is the strong coupling and C is the color factor.

This approach has been applied to the description of the polarization in the K^-p reaction and successfully reproduced its main features at $2C\alpha_{\mathrm{s}} = 5.0$ and the s quark mass $m_s = 0.5$ GeV [7].

Due to some peculiarities of the HERMES experiment, the polarization was not measured in the traditional form of the dependence on $x_{\mathrm{F}} = 2p_z/\sqrt{s}$ (p_z is the longitude component of the detected particle momentum, and $\sqrt{s}$ is the total CMS energy). Therefore, we have expressed the model in terms of the light cone variable ζ that the available data depend on [32]. It is defined as

$$\zeta_{i(f)} = \frac{E_{i(f)} + p_{zi(f)}}{E_{\mathrm{b}} + p_{z\mathrm{b}}}\,; \tag{2}$$

here the subscript b denotes the beam. We note that ζ is invariant under Lorentz boosts being useful in its application.

According to the recipes given in [7], one should move to a frame in which the magnitudes of the initial and final s quark momenta are the same (originally called the S-frame). It is reached by performing a Lorentz transformation along the proton momentum. For this purpose, one can write

$$(p_i \cdot p_f) = p^2(1 - \cos\theta) + m_s^2\,, \tag{3}$$

$$p_{\mathrm{T}f} = p_{\mathrm{T}} = p\sin\theta\,, \tag{4}$$

where $p_{i(f)}$ are the 4-momenta of the scattering quark, $p_{\mathrm{T}f}$ is the transverse momentum of the scattered quark in the center-of-mass frame of the K^-p reaction, while $p = \sqrt{E^2 - m_s^2}$, p_{T} and θ refer to the S-frame.

On the other hand, using (2) leads to

$$(p_i \cdot p_f) - m_s^2 = \frac{m_s^2}{2}\frac{(\zeta_i - \zeta_f)^2}{\zeta_i\zeta_f} + \frac{1}{2}\left[p_{\mathrm{T}i}^2\frac{\zeta_f}{\zeta_i} + p_{\mathrm{T}f}^2\frac{\zeta_i}{\zeta_f}\right] + (\mathbf{p}_{\mathrm{T}i} \cdot \mathbf{p}_{\mathrm{T}f})\,, \tag{5}$$

where $(\mathbf{p}_{\mathrm{T}i} \cdot \mathbf{p}_{\mathrm{T}f})$ is the ordinary scalar product of the transverse momentum vectors.

Neglecting, as a first approximation, the transverse momentum of the incident quark ($p_{\mathrm{T}i} = 0$), after some algebra, one can obtains from (3)–(5)

$$\cos\frac{\theta}{2} = \xi\frac{V_{\mathrm{T}}^2}{(1-\xi)^2+V_{\mathrm{T}}^2}\,, \tag{6}$$

$$V = \frac{(1-\xi)^2+V_{\mathrm{T}}^2}{2\sqrt{\xi}\sqrt{(1-\xi)^2+(1-\xi)V_{\mathrm{T}}^2}}\,, \tag{7}$$

with the variables $V_{(\mathrm{T})}$, and ξ defined by

$$V_{(\mathrm{T})} = \frac{p_{(\mathrm{T})}}{m_s}\,, \quad \xi = \frac{\zeta_f}{\zeta_i}\,. \tag{8}$$

By using relations (6) and (7), (1) can be rewritten

$$P(\xi, V_{\mathrm{T}}) = -\frac{2C\alpha_{\mathrm{s}}V}{1+V^2\cos^2\theta/2}\frac{\sin^3\theta/2\ln(\sin\theta/2)}{\cos\theta/2}\,. \tag{9}$$

Note that the minus sign in (9) appeared to satisfy the rule of DeGrand and Miettinen in the region of our interest ($\xi < 1$).

3 Calculations and results

Our calculations concern the polarization in the region of $0.25 \lesssim \zeta_\Lambda \lesssim 0.5$, which, according to [32], corresponds to the events of $x_{\mathrm{F}} > 0$ in the CMS frame of the $\gamma^* p$ reaction (current fragmentation). The procedure is now straightforward. In the model discussed above, one substitutes the K^- meson by the intermediate quasi-real photon γ^*. Since the hyperons considered are produced in the photon fragmentation region, we assumed that the Λ^0 kinematic is determined here in the main by the quarks originating from the photon. The $(ud)_0$ diquarks are supposed to come mostly from the proton target. The polarization process is schematically shown in Fig. 1. Note that a similar diagram, corresponding to the s quark scattering off the scalar diquark $(ud)_0$, also appears in the QRM [14] when one calculates the polarization in the $K^- p$ reaction; however, the interaction is chosen to be scalar.

Within the present approach, one needs to know the ζ_i distribution of the incident s quarks originating from the quasi-real photons emitted by the positron beam. To find it, we used the PYTHIA 6.2 program [36], adopting thus the positron-to-quark transition mechanisms implemented therein. The distribution obtained is shown in Fig. 2 (scattered plot) together with its fit (solid line).

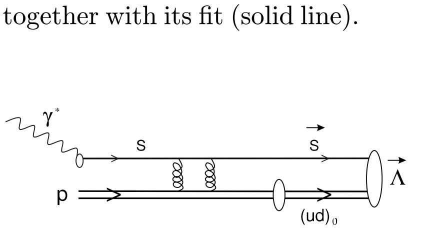

Fig. 1. A schematic diagram of the Λ^0 polarization process in quasi-real photoproduction. The s quarks originating from the photon scatters off the target color field, thus getting polarized, and they form the final hyperon recombining with $(ud)_0$ diquarks from the proton target. An arrow over a letter indicates the polarization

The final s quark kinematics was determined according to the following:

$$\zeta_f = \frac{m_s}{m_\Lambda}\zeta_\Lambda, \qquad V_{\mathrm{T}} = \frac{p_{\mathrm{T}\Lambda}}{m_\Lambda}\,, \tag{10}$$

where ζ_Λ and $p_{\mathrm{T}\Lambda}$ refer to the detected Λ^0 hyperons. Let us omit in the sequel the index Λ. The relations in (10) define the quark momenta as fixed fractions of the corresponding final hyperon momenta. In particular, the direction of the transverse momentum of the s quark is assumed to point in most cases in the direction of $p_{\mathrm{T}\Lambda}$ [6]. This is, of course, only an approximate picture. One should take into account that the quarks are just constituents of the hyperon but not free. In fact, a momentum component of a quark inside a hadron is not fixed but has an intrinsic distribution.

Note that there should be a threshold for the Λ^0 production in the region of $\zeta > 0.25$ initiated by the incoming quarks due to the fact that the undetected hadron system always exists and also carries away some part of the energy. In other words, not all the ζ_i events will contribute to the $\zeta > 0.25$ region. Thus, in the calculations, we took into account only those quarks that have $0.5 \leq \zeta_i \leq 1$ (hatched area in Fig. 2).

As the experimental ζ dependence of the polarization is available integrally over p_{T}, we additionally introduced averaging over the transverse momentum of the detected Λ^0. In this case, the polarization was determined as

$$P_\zeta = \int \mathrm{d}\zeta_i\,\mathrm{d}p_{\mathrm{T}}h(p_{\mathrm{T}})P\left(\frac{\zeta}{\zeta_i}, p_{\mathrm{T}}\right)f(\zeta_i)\,. \tag{11}$$

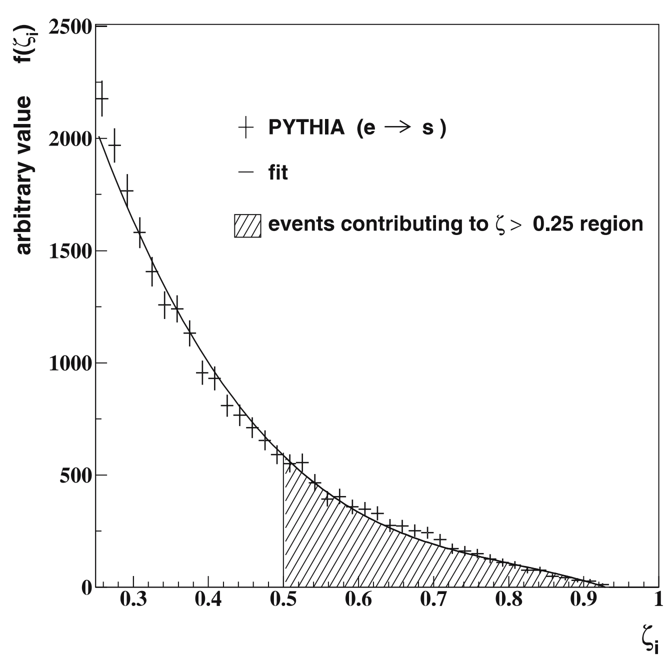

Fig. 2. The ζ_{i} distribution of the quarks originating from the positron beam according to the PYTHIA program (*scattered plot*). The corresponding fit is presented by the *solid line*. Events assumed to contribute to the region of $\zeta > 0.25$ are hatched

Here, $h(p_\mathrm{T})$ and $f(\zeta_i)$ are the p_T and ζ_i distribution functions of the detected Λ^0 and the incident quarks, respectively; $P(\zeta/\zeta_i, p_\mathrm{T})$ is the polarization defined by (9).

For similar reasons, we determined the p_T dependence of the polarization as

$$P_{p_\mathrm{T}} = \int \mathrm{d}\zeta_i \,\mathrm{d}\zeta g(\zeta) P\left(\frac{\zeta}{\zeta_i}, p_\mathrm{T}\right) f(\zeta_i)\,, \qquad (12)$$

where $g(\zeta)$ is the ζ distribution function of the detected hyperons.

Using (11) and (12), we carried out the calculations. Since many arguments of the model are qualitative, we restricted our considerations only to the regions covered by the experiment. Therefore, we used a typical ζ distribution of the detected Λ^0 in the interval $0.25 \le \zeta \le 0.5$ (see Fig. 3).

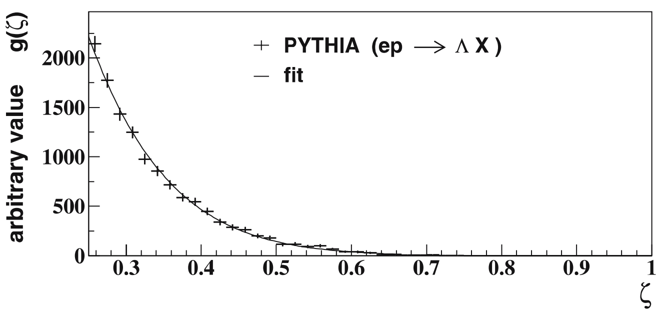

Fig. 3. The ζ distribution of Λ^0 hyperons produced in inclusive *ep*-reaction at the 27.6 GeV positron beam energy according to the PYTHIA program (*scattered plot*). The corresponding fit is presented by the *solid line*

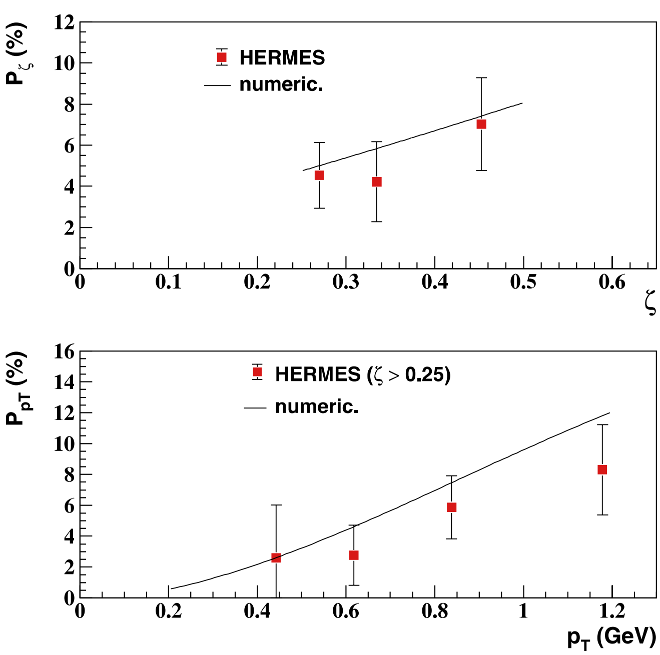

Fig. 4. Numerical results (*lines*) in comparison with the HERMES data (*solid points*). The ζ (p_T) dependence of the Λ^0 polarization is presented in the *upper* (*lower*) *panel*. The data are taken from [32]

For $h(p_\mathrm{T})$, we adopted the one obtained by HERMES ($0.2\,\mathrm{GeV} \le p_\mathrm{T} \le 1.2\,\mathrm{GeV}$) [37]. Note that all the distributions were prenormalized to unity. As the free parameter values, we have taken $2C\alpha_\mathrm{s} = 5.0$ and $m_s = 0.5\,\mathrm{GeV}$.

The numerical results in comparison with the HERMES data are shown in Fig. 4. One can see that the experiment is reasonably reproduced.

4 Conclusion

The results obtained should be regarded only as qualitative. We neglected the transverse momentum of the incident quarks ($p_{\mathrm{T}i}$), while, certainly, a strict consideration would require taking it into account. However, for the goals the present work aimed at, such an approximation reflects the general tendencies. It would be fair to expect a relatively narrow $p_{\mathrm{T}i}$ distribution for the events contributing to the region of $\zeta > 0.25$. To find the ζ_i distribution, we used the PYTHIA program, which gives, in turn, qualitative rather than quantitative predictions. We did not take the contributions from the heavier resonances, such as Σ^0, Ξ and Σ^*, into account; their values are presumably considerable in Λ^0 polarization [25, 38, 39]. A difficulty is also caused by the impossibility to derive the running coupling constant α_s from the HERMES data.

In fact, the calculations by (11) and (12) have been carried out similarly with the quark recombination model [14]; the latter describes the polarization in a more quantitative manner. In the QRM, the central point is the squared subprocess amplitude averaged over the Bjorken variables in the initial and final states, and their roles, in our case, were played by ζ_i and ζ. A substantial distinction between the QRM and the present quark scattering approach (QSM) is the interaction. For the QRM, it has been assumed to be a scalar force, while the QSM calculations are based on QCD. Thus, it seems to be attractive alternatively to specify the QRM interaction by the color one. Doing it could be regarded as a further development of the present approach. It will include, in particular, the transverse momentum of the incident quarks, the structure functions of the projectile as well as the outgoing hyperon instead of the approximations of (10). It will also more explicitly show the underlying mechanisms introducing additional parton–parton subprocesses, which is necessary for a more or less correct determination of the range of validity of the QSM.

An estimation of the contributions of the heavier resonances is in progress now.

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