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Quark scattering model of the transverse Λ^0 polarization and quark recombination approach

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Abstract – The transverse Λ^0 polarization in high-energy inclusive photoproduction at the current fragmentation is calculated in the framework of the quark scattering model. Transverse motion of the incident quarks as well as the leading contribution of heavier resonances are taken into account. Similar results are obtained within the quark recombination approach. All the calculations are compared with experiment.

Introduction. – The problem of the Λ^0 polarization in hadron-hadron reactions at high energies remains challenging in spite of the thirty years have passed since it was discovered [1]. Being produced in pN collisions at 300 GeV proton beam energy, Λ^0-hyperons were found to be highly polarized while neither the beam nor the beryllium target possessed any initial polarization. Its direction was, in accordance with the spatial parity conservation, opposite to the unit vector $\boldsymbol{n} \propto [\boldsymbol{p}_b \times \boldsymbol{p}_\Lambda]$ ($\boldsymbol{p}_b$ and $\boldsymbol{p}_\Lambda$ are the beam and hyperon momenta, respectively), which is normal to the production plane or, in other words, transverse to the direction of this particle's motion.

The phenomenon has attracted much attention to studies of the polarization experimentally, using a variety of beam hadrons and targets at different kinematic regimes, as well as to its theoretical explanations. Thus, further experiments on pN collisions in a wide range of the beam energies have been carried out [2]. It has also been examined in the inclusive meson-induced reactions $K^-p \to \Lambda X$ [3], $\pi^- N \to \Lambda X$ and $K^+ N \to \Lambda X$ [4–6]. Processes, where hyperons themselves acted as projectiles have been under consideration as well, for example $\Sigma^- N \to \Lambda^0 X$ [7]. Besides, the polarization in the reactions induced by photons and leptons is also of great interest [8–12]. The experimental status of spin physics is reviewed, *e.g.*, in ref. [13].

Although there have been the relatively large amount of experimental information, no model is still elaborated convincingly to account for the available data from a unified point of view. The existing ones exhibit varying success in reproducing experiment (see, *e.g.*, refs. [14–26] and the references therein). A part of the calculations carried out herein are based on the model proposed by Szwed according to which the polarization of Λ^0-hyperons is attributed to the polarization of its valence strange quarks undergoing multiple scattering in the external color field [16]. This idea has been applied to description of the polarization in the K^-p reaction and allowed to sufficiently reproduce its main features [17]. In a recent paper we have shown that the experimental data of the HERMES collaboration on the transverse polarization of Λ^0-hyperons inclusively produced in quasi-real photoproduction at the current fragmentation [12] can be accommodated by the strange quark scattering model [27]. In this letter we present basically the same calculation procedure, however improved by taking the transverse momentum of the initial quarks as well as the contribution of Σ^0, Σ^* and Ξ resonances into account. The range of energies possessed by these quarks is widened.

As a notable addendum, we also present the corresponding results obtained within the quark recombination approach originally proposed to account for meson production probabilities in pp collisions [28] and had then been employed to calculate polarizations of different hyperons in a variety of high energy hadron-hadron reactions [29].

Quark scattering model. – Since the model has been described in details in ref. [27], let us outline here only its essential ingredients.

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$$J^{lijk}_{D(I)} = G^2_\Lambda(r_3,r_4,x_F,p_T)\otimes\sigma^l_{D(I)}(r_1,r_2,r_3,r_4,x_F,p_T)\otimes f^\gamma_{q_k}(r_1)\otimes f^p_{(q_iq_j)_l}(r_2)\otimes\Delta^3\otimes\Delta^4. \quad (5)$$

The HERMES data, our calculations are compared with, have been reported as the p_T and ζ dependences, where p_T is the transverse momentum of Λ^0 by magnitude and ζ is defined as follows:

$$\zeta_k = \frac{E_k + p_{Lk}}{E_e + p_{Le}}, \quad (1)$$

here E_k and p_{Lk} (E_e and p_{Le}) are the energy and longitudinal momentum of the particle k (of the positron beam). Note that here and henceforth we write the kinematic quantities corresponding to the produced Λ^0 hyperon without the index Λ (*i.e.*, ζ and p_T instead ζ_Λ and $p_{T\Lambda}$).

The dependence of the polarization on ζ is determined as

$$P_\zeta = \int \mathrm{d}p_T \int_\zeta^1 \mathrm{d}\zeta_i \int_0^{p_T} \mathrm{d}p_{Ti} h(p_T) P\left(\frac{\zeta}{\zeta_i}, p_{Ti}, p_T\right) F(\zeta_i, p_{Ti}), \quad (2)$$

where $h(p_T)$ is the p_T distribution function of Λ^0's taken from ref. [30], $F(\zeta_i,p_{Ti}) = f(\zeta_i)w(p_{Ti})$ with $f(\zeta_i)$ and $w(p_{Ti})$ being the ζ_i and p_{Ti} distribution functions of the incident quarks, $P(\zeta/\zeta_i,p_{Ti},p_T)$ is the polarization of the quarks in the scattering subprocess a procedure of obtaining its explicit form is given in ref. [27].

The dependence on p_T similarly reads

$$P_{p_T} = \int \mathrm{d}\zeta \int_\zeta^1 \mathrm{d}\zeta_i \int_0^{p_T} \mathrm{d}p_{Ti} g(\zeta) P\left(\frac{\zeta}{\zeta_i}, p_{Ti}, p_T\right) F(\zeta_i, p_{Ti}), \quad (3)$$

where $g(\zeta)$ is the ζ distribution function of Λ^0-hyperons. The integrations over ζ and p_T were carried out only in the region covered by the experiment ($0.25 \leqslant \zeta \leqslant 0.5$ and $0.2\,\mathrm{GeV} \leqslant p_T \leqslant 1.2\,\mathrm{GeV}$). Fits of $f(\zeta_i)$ and $g(\zeta)$ are given in ref. [27]. We found the function $w(p_{Ti})$ by means of the program PYTHIA 6.2 [31], according to which it can be presented as $w(p_{Ti}) = 15.8\,p_{Ti}\exp\left(-p^2_{Ti}/0.127\right)$. Using eqs. (2) and (3) we carried out the calculations with keeping all the values of the free parameters already fixed in ref. [27]. Additionally, the contribution of Σ^0, Σ^* and Ξ resonances were taken into account exactly in the way considered in ref. [32]. Its average value constitutes 13.3% of the total polarization. The calculations in comparison with the data of HERMES are shown in fig. 1. Note that though the dependence on p_T is reasonably reproduced, the numerical result corresponding to the ζ-dependence is not in such a good agreement with the experiment as can be seen in ref. [27]. Partly, this is due to the choice of the region of the integration over ζ_i. In the present letter, the region is not fixed and therefore includes additional possibilities of the Λ^0 production. Partly, this is caused by taking into consideration the transverse motion of the incident quarks.

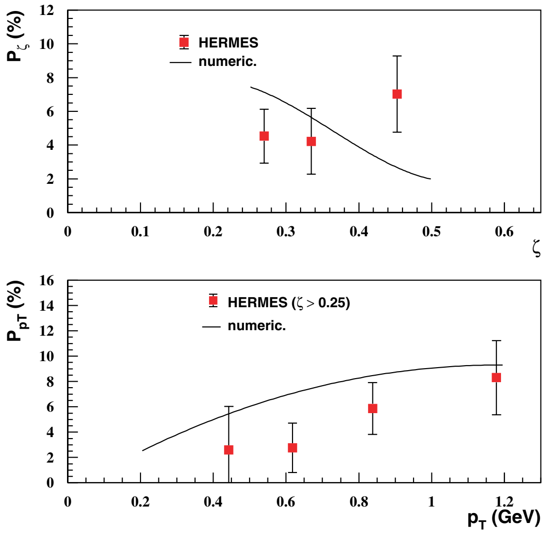

Fig. 1: Numerical results obtained within the quark scattering model (lines) in comparison with the HERMES data [12] (solid points). The ζ-dependence (p_T-dependence) of the Λ^0 polarization is presented in the upper (lower) panel.

Quark recombination model. – For more details of the calculations given below, see ref. [29].

The quark recombination model (QRM) can be straightforwardly extended to the Λ^0 photoproduction by replacing the structure function of the initial hadron by that of the photon [33]. Then, this reaction may be considered as recombination of a quark q directly coming from the photon with an appropriate proton's diquark $(qq)_l$ (the index l indicates the spin states, we take into account only the scalar ($l=0$) and vector ($l=1$) diquarks). Note that in this section, to distinguish between the target and current fragmentation regions, we will use the variable $x_F = 2p_L/\sqrt{s}$, where p_L is the longitudinal momentum of the observed particle, $\sqrt{s}$ is the total center-of-mass energy. Thus, the region of our interest refers to the range $0 < x_F < 1$.

Using the recipes given in ref. [29], one can find the following formula for the polarization [34]:

$$P_{x_F,p_T} = \frac{\sum\limits_{i,j,k}\sum\limits_l R_l J^{lijk}_D}{\sum\limits_{i,j,k}\sum\limits_l J^{lijk}_I}, \quad (4)$$

where R_l are the free parameters and the corresponding sum runs over the scalar ($l=0$) and vector ($l=1$) cases.

See eq. (5) *above*

$J^{lijk}_{D(I)}$ is given by eq. (5), where $r_k=(x_k, y_k, z_k)$ are the momentum fractions carried by the partons with respect to the three independent directions (x, y, z), the x-axis determines the beam direction, $k=1,2,3,4$, the indices $k=1,2$ and $k=3,4$ are reserved for the initial and final states respectively, G_Λ is the light cone wave function of Λ^0, $\sigma^l_D(r_k, x_F, p_T)$ $(\sigma^l_I(r_k, x_F, p_T))$ is a quantity proportional to difference between (sum of) spin-up quark scattering and spin-down quark scattering cross sections, or schematically $\sigma^l_{D(I)}(r_k, x_F, p_T) \propto [\sigma_{q\uparrow} - (+)\sigma_{q\downarrow}]$ [29], $f^p_{(q_iq_j)_l}(r_2)$ are the momentum distribution functions of the $(q_iq_j)_l$ diquarks in the proton, $f^\gamma_{q_k}(r_1)$ are the structure functions of the photon, Δ^3 and Δ^4 are the delta-functions providing energy-momentum conservation. The sum referring to the indices i, j, k is rather symbolic and runs only over the following combinations of the quarks and diquarks to form the final Λ^0: $u+(ds)_0$, $d+(us)_0$, $s+(ud)_0$, $u+(ds)_1$ and $d+(us)_1$. The sign $\otimes$ denotes the convolution in the r-space and is defined as

$$a(r_a) \otimes b(r_b) = \int \left[\prod_{m=1}^{4} \mathrm{d}x_m \mathrm{d}y_m \mathrm{d}z_m / x_m \right] a(r_a) b(r_b).$$

Using eqs. (4) and (5) we carried out the calculations. All the values of the free parameters used have been already fixed in ref. [29], for instance $R_0 = 2.5\,\mathrm{GeV}$ and $R_1 = -5.6\,\mathrm{GeV}$. The photon structure functions $f^\gamma_{q_k}(r_1)$ are taken from ref. [33]. For the diquark distribution functions of the proton $f^p_{(q_iq_j)_l}(r_2)$, we adopted those from ref. [35]. Note that we assumed the functions for the scalar and vector diquarks to coincide, except the one for $(ud)_0$ due to the valence character of both u and d quarks forming it. Though these functions depend on the momentum transfer squared Q^2, the calculations insignificantly change under variations of Q^2. Herein, it is fixed at $Q^2 = 8\,\mathrm{GeV}^2$. The condition of the hyperon photoproduction at $x_F > 0$ was fulfilled by imposing the inequality $x_1 > x_2$, which simply means that each quark coming from the photon will be faster than the corresponding picked up diquark.

The numerical results are shown in fig. 2.

First of all, one can see that the polarization is positive. The p_T-dependence of the polarization, calculated at $x_F = 0.1$, $x_F = 0.2$ and $x_F = 0.4$, grows roughly linearly, which is also typical for other reaction. We have averaged the calculated x_F-dependence over the p_T distribution of Λ^0-hyperons produced at HERMES [30]. Here, one can see the qualitative coincidence with the corresponding calculations within the quark scattering model (the ζ-dependence). However, it should be recalled that the HERMES data are reported not as the traditional x_F-dependence but as the dependence on ζ. There is an arbitrariness in the correlation between x_F and ζ. Unlike x_F, the variable ζ is just an approximate measure of whether the hyperons were produced in the current or target fragmentation regions. For this reason, we

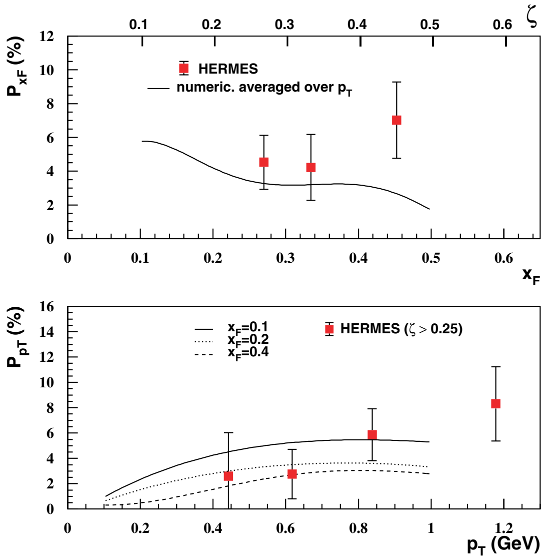

Fig. 2: Numerical results obtained within the quark recombination model (lines) in comparison with the HERMES data [12] (solid points). The x_F-dependence of the Λ^0 polarization (upper panel) is averaged over the p_T distribution of Λ^0-hyperons. The p_T-dependence is calculated at $x_F = 0.1$ (solid line), $x_F = 0.2$ (dotted line) and $x_F = 0.4$ (dashed line).

compared the calculations only with the experimental points at $\zeta > 0.25$ as they more reliably correspond to the current fragmentation region [12].

Here we did not take into account the contributions of the heavier resonances since it is relatively small and induces no qualitative change of the final results.

Conclusion. – The transverse polarization of Λ^0-hyperons in inclusive photoproduction at $x_F > 0$ is calculated within the quark scattering model, improved by taking the transverse momenta of the incident quarks as well as the leading contribution of the heavier resonances into account. The polarization is also tackled in the framework of QRM. The calculations are compared with the recent experimental data of HERMES.

All the numerical results presented in this letter must be regarded only as a qualitative reproduction of the experiment because of, at least, the following reasons. The quark scattering model is based on QCD containing the strong coupling constant as a free parameter. Only the main subprocess $s+(ud)_0$ was considered. The Monte Carlo simulations were used. There are also difficulties connected to QRM. The arbitrariness in the correlations between ζ and x_F takes place. No information on the momentum transfer was available at the experiment, while the parton distribution functions depend on Q^2. The distributions of the scalar and vector diquarks in the proton were assumed to have the same form.

The quark scattering model seems to provide more detailed view of the dynamic of the polarization, however it certainly requires further analysis.

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