QUARK RECOMBINATION MODEL FOR POLARIZATIONS IN INCLUSIVE HYPERON PRODUCTIONS AT HIGH ENERGY

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We investigate the transverse polarization of hyperons produced by the photon induced reactions using the quark recombination model. This model reproduces polarizations of hadrons produced by the hadron-hadron collisions and accounts for the origin of the empirical rule by DeGrand and Miettinen. We find significant polarizations in the hyperon photoproduction by applying this model to the $\gamma N \rightarrow \Lambda (\Sigma^0) + X$ reaction.

1 Introduction

Significant transverse polarizations and analyzing powers of inclusively produced hadrons $\Lambda$ in unpolarized hadron-hadron collisions are observed at high Feynman $x_F (= 2p_L/\sqrt{s}, p_L$ is the longitudinal momentum of the observed particle) and low transverse momentum $p_T$ region against predictions of the perturbative QCD. These data indicate some non-perturbative mechanism being intact for the production of the polarization. Several models are proposed to account for these phenomena. It is generally expected that the spin polarization is generated by some soft processes in the initial state and/or final state thorough the hadron-hadron collision.

Yamamoto et al. have constructed the quark recombination model to explain the generation of the polarization. In this model, a final state hadron is produced by the simple recombination of relativistic quarks and/or diquarks, and polarizations are generated by the scalar confining force through the hadronization process in purely non-perturbative way. It was shown that this model reproduces the empirical rule of DeGrand and Miettinen(DM), and provides the polarizations in agreement with the experimental data. In the framework of this model, we naturally expect non-vanishing polarizations even in the hyperon photoproduction. Here, we investigate polarizations of the hyperons in the photon induced reaction using the quark recombination (QRC) model.

2 Quark Recombination Model

Let us briefly introduce the quark recombination model. It is assumed that a fast valence quark (or diquark) directly coming from the projectile hadron picks up slow quarks created by the hadronization to form the finale state hadron. The particle production at high $x_F$ is dominated by this direct process, while the middle and small $x_F$ hadron production are described by the standard fragmentation, in which
all the quarks are randomly created by the string breaking. Hence, the produced hadron at the high $x_F$ contains some information on the valence quark structure of the beam hadron. In fact, the polarization of the hyperon in the final state reflects the spin structure of the beam hadron (see assumption [4]).

Our model is based on the following assumptions:

1. The produced hadron is formed by direct recombination process, since significant polarizations are observed in the high $x_F$ region.
2. Each parton which participates in this reaction has the intrinsic transverse momentum distribution.
3. Quark and diquark are recombined by the scalar confinement interaction in the hadronization process.
4. SU(6) spin-flavor symmetry is assumed for the initial and final state hadron structure.

Now we concentrate on the Λ hyperon production in the proton-proton collision. In this case, the SU(6) spin-flavor symmetry tells us that the valence $(ud)$-diquark from the beam proton picks up a slow $s$-quark in order to form the final state Λ. The spin of the Λ is determined by the $s$-quark spin. Thus, the polarization of the Λ, $P_N(Λ)$, is defined as

$$P_N(Λ) = \frac{\sigma(Λ \uparrow) - \sigma(Λ \downarrow)}{\sigma(Λ)} \equiv \frac{\sigma(s \uparrow) - \sigma(s \downarrow)}{\sigma(Λ)}.$$ 

where the spin direction is fixed by $p_{beam} \times p_Λ$.

The Λ production probability in the Infinite Momentum Frame (IMF) is given by

$$S_{p→Λ} = \int [dx_idy_idz_i/x_i] G_Λ(x_i, x_4, y_3, y_4, z_3, z_4)$$

$$\times |M(x_i, y_i, z_i)|^2 f_s(x_2, y_2, z_2) G_{(ud)^0/p}(x_1, y_1, z_1) \Delta^3 \Delta^4$$

where we choose the $x$-axis as the beam direction and $z$ as the orientation of the Λ spin in the final state, $\Delta^3$ and $\Delta^4$ express the delta functions which correspond to energy-momentum conservation in this process. $G_{(ud)^0/p}$ is the momentum distribution of the $(ud)$-diquark in the projectile proton. We assume the following form:

$$G_{(ud)^0/p}(x_1, y_1, z_1) = q_{(ud)^0/p}(x_1) e^{-(y_1^2+z_1^2)}$$

where the longitudinal momentum distribution $q_{(ud)^0/p}(x_1)$ is the $(ud)$-diquark distribution function in the proton taken from Ref. [8]. On the other hand, the transverse $y$ and $z$ momentum distributions are assumed to be the Gaussian form with the average transverse momentum being about 400 MeV. $f_s$ is the momentum distribution of the picked-up $s$-quark;

$$f_s(x_2, y_2, z_2) = \theta(x_1 - x_2) e^{-(y_2^2+z_2^2)}.$$ 

where we take the Gaussian transverse momentum distribution. We assume that the picked up $s$-quark is slower than the $(ud)$-diquark, which is expressed by $\theta$-function.
Figure 1. Λ polarization in the pp collision at $p_T = 1\text{GeV}/c$ with the experimental data.

$P_N(\Lambda) = R_0 \frac{\int [dx_i dy_i dz_i/x_i] G^2_\Lambda \sigma_{\text{dep.}} f_s G_{(ud)}^{\nu/p} \Delta^3 \Delta^4}{\int [dx_i dy_i dz_i/x_i] G^2_\Lambda \sigma_{\text{ind.}} f_s G_{(ud)}^{\nu/p} \Delta^3 \Delta^4}$

(6)

where the spin independent cross section is

$\sigma_{\text{ind.}} = (x_F x_4 x_2) \left( \frac{x_F x_4 + x_2}{x_F x_4 x_2} m_2 \right)^2 + \left( \frac{x_F x_4 y_2 - x_2 y_4}{x_F x_4 x_2} p_t \right)^2$

(7)

and the spin dependent one

$\sigma_{\text{dep.}} = -(x_F x_4 x_2) \left( \frac{x_F x_4 y_2 - x_2 y_4}{x_F x_4 x_2} p_t \right)$

(8)

Note that, if we took the vector interaction instead of the scalar, the spin dependent part of the cross section would vanish in the IMF. $R_0$ in Eq. (6) is a free parameter and will be fixed to reproduce the experimental data of the Λ polarization.

Similarly, we can obtain the formula for the polarization of $\Sigma^0$ production. Since the Σ hyperon has the isospin 1, $\Sigma^0$ hyperon is formed by the recombination of a fast spin-1 ud-diquark and a slow s-quark. We need another parameter $R_1$ to be fixed by the Σ polarization data. From experimental data for Λ and Σ, we determine $R_0 = -12 \text{ GeV}$ and $R_1 = 50 \text{ GeV}$. Our results are shown in Fig. 1 and 2 for the Λ and Σ polarizations, which are consistent with experiments. We can calculate the polarization of other hadrons, e.g. Ξ, which is also in good agreement with experiments.
3 Photon induced hyperon production

In our model, polarizations are generated by the non-perturbative hadronization process. Therefore, even in the photon induced reaction, we expect finite polarizations of the produced hyperons, because the hadronization process itself is independent of the beam. Let us consider the unpolarized $\gamma$-hadron reaction as schematically shown in Fig. 3. It is known that the real photon has the hadronic (vector meson) structure, since the real photon has enough time to turn into a $\bar{q}q$ system. In fact, the quark distribution of the real photon observed by the deep inelastic lepton-photon scattering contains the substantial hadronic components. We show in Fig. 4 the parametrization of the quark distribution of the real photon taken from ref. [9].

We apply our model to the photoproduction of hyperons. We replace the diquark distribution of the proton in the previous formula Eq. (6) with the quark distribution $G_{q/\gamma}$. In this case, the $u$ (or $d$ or $s$)-quark picks up a diquark to form the $\Lambda$ or $\Sigma^0$ hyperons. Notice that both spin-0 and spin-1 diquark recombination processes contribute to this reaction. We get the following expression for the $\Lambda$ polarization in the photon induced reaction,

$$P_N(\Lambda) = \sum_l R_l \int \frac{dx_1dy_1dz_1}{x_1} G_{\Lambda/\gamma}^2 \sigma_{\text{dep.}}(\gamma q) G_{q/\gamma} \Delta^3 \Delta^4$$

where $l$ runs over possible combinations of quarks and diquarks.

We show in Fig. 5 and 6 our results for the $\Lambda$ and $\Sigma$ polarizations in the $\gamma N$ reaction. The magnitude of the polarization is similar with that of the proton-proton collision. These theoretical predictions will be clarified by future experiments such as the PEARL facility.
4 Summary

In conclusion, we have studied the spin polarizations of the hyperon photoproduction based on the quark recombination model. Our model may be applicable for the process with the photon beam, whose energy is larger than about 5 GeV, where the quark degrees of freedom are essential rather than the hadronic components. We have reproduced various polarizations in the inclusive hyperon production in the hadron-hadron collisions with the model parameters being fixed to reproduce the absolute magnitudes of the polarizations of Λ and Σ. With these parameters we have found that about 20 \( \sim \) 30\% negative polarizations of Λ in the photon induced reaction, which will be tested by future experiments. It is also possible to extend the present model to the \( e^+e^- \) annihilation process. However, the polarization almost vanishes in the \( e^+e^- \rightarrow \Lambda + X \) case, because the intrinsic transverse momentum distribution of the initial quark can be neglected in this case.

![Figure 5. Λ Polarization in the \( \gamma N \) reaction. Experimental data are taken from ref. [10].](image1)

![Figure 6. Σ Polarization in the \( \gamma N \) reaction.](image2)

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