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Nuclear and hadronic reaction mechanisms producing spin asymmetry

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Abstract. We briefly review concept of the quark recombination (QRC) model and a general success of the model. To solve the existing problem, so called anomalous spin observables, in the high energy hyperon spin phenomena, we propose a mechanism; the primarily produced quarks, which are predominantly u and d quarks, act as the leading partons to form the hyperons. Extension of the quark recombination concept with this mechanism is successful in providing a good account of the anomalous spin observables. Another kind of anomaly, the non-zero analysing power and spin depolarization in the Λ hyperon productions, are also discussed and well understood by the presently proposed mechanism. Recently, a further difficulty was observed in an exclusive $\Lambda K^+ p$ production and we will indicate a possible diagram for resolving it.

Keywords. Quark recombination models; hadrons; spin polarization.

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1. Introduction

It has been generally established that, in contrast to the perturbative QCD predictions, spin effects in the hadron collisions are large over a wide incident energy range [1] even at extremely high energies such as 2000 GeV [2]. Among them, the hyperon spin polarization mechanisms have been well studied with the various theoretical models assuming a soft scattering process [3–5]. The left-right asymmetries of $\pi^{\pm,0}$ from the inclusive $\vec{p}p$ collisions [6] have also attracted attention and the observed characteristics have been well described by those theoretical calculations [3–5].

Essential results of the spin polarizations in the inclusive hadron reactions are well interpreted by the parton recombination picture proposed by DeGrand and Miettinen (DM) [3]. However, the DM model predicts only order of magnitudes of the hadron spin observables, and does not give spin observables as functions of x_F nor P_T, longitudinal (Feynman) and transverse momentum variables, respectively. Hence we have developed the so-called microscopic quark recombination (QRC) model in the relativistic framework [7]. We have demonstrated the general success of the model for most of the existing high-energy inclusive experimental data [7]. Then we have concluded that the QRC formalism itself contains the dynamics producing spin asymmetry, which was assumed as an empirical rule in the DM model.

In the following, we summarize first the concept of the DM model and the QRC model to show what the normal cases are in order to define 'anomalous' or 'puzzling' spin observables. In these models, the projectile makes a hard collision with the target and one of the fragments (leading parton which can be a quark or a diquark), which moves fast with the original velocity and has a color, makes a color flux behind with its colored counterpart. As the color flux is prolonged by the initial parton momentum, the pair creation takes place somewhere in the color flux and the leading parton together with one of the created pair form a pre-hadron. At the time the pre-hadron is formed, the leading (valence) parton is moving fast and the picked up (sea) parton which is one of the created pair is moving slow. They are pulled by each other, decelerated or accelerated respectively, towards the averaged velocity to form the hadron eventually to be observed experimentally.

The confining force takes place in this momentum averaging process, which causes the spin dependent effect (Thomas precession) and produces the spin polarization of the ejectile hadron. DeGrand and Miettinen brought the effect into an empirical rule [3] that parton(s) moving fast (slow) carries up (down) spin mostly, respectively. We shortly call it as 'fast-spin-up and slow-spin-down' in our work. Finally the sign of the spin polarization is determined by two ingredients; one is the dynamics of the spin dependent effect and the other is the wave functions of the projectile and ejectile hadrons, for which the DM model and the QRC model use the SU(6) valence quark model.

We have shown in ref. [8] that the spin dependent effect can be formulated in a form of spin-orbit coupling type interaction if we assume the rearrangement interaction being a local (momentum independent) one. It is of course not proper assumption and we know that the interaction is of strongly non-local (momentum dependent). For the case, we have indicated [8] acting of a so-called dynamical (momentum dependent) spin-orbit interaction through the rearrangement collision process, which is induced by the deceleration or acceleration of participating quark partons.

In the ordinal nuclear reaction processes, the similar (deceleration or acceleration) dynamics also has been found. One of the examples is in the (p, α) reaction, of which angular distribution shows a strong j-dependence, where $j = l \pm 1/2$ is the total spin of the three nucleons, to be picked up through collision, in the bound state of target nucleus. The left-right asymmetry (analysing power) of the (p, α) reaction with spin polarized protons also shows the j-dependence. We have indicated [9] the two ingredients for its source: the spin-orbit distortion in the incident proton-channel and the similar deceleration or acceleration process in the three-nucleon rearrangement collision. The same things play an important role in producing spin asymmetry induced by the other nucleon-transfer reactions such as (d, p), (p, t), (^{3}He, d) etc.

In back to the high energy hadron production reactions, the DM model consists of a leading parton (projectile valence quark (s)) with high velocity and an associated parton (sea quark (s)) with low velocity. The model then predicts correct signs and rough magnitudes of hadron spin polarizations for valence quark reactions and no spin polarization for no-valence quark reactions such as $p \to \bar{\Lambda}$, $\Sigma^- \to \bar{\Lambda}$ and $p \to \Omega^-$ (completely strange baryons), where we use the notation e.g. $p \to \bar{\Lambda}$ for inclusive reactions such as pp and pA collisions leading to $\bar{\Lambda}X$. The cases to be described by the mechanism explained above are the normal ones.

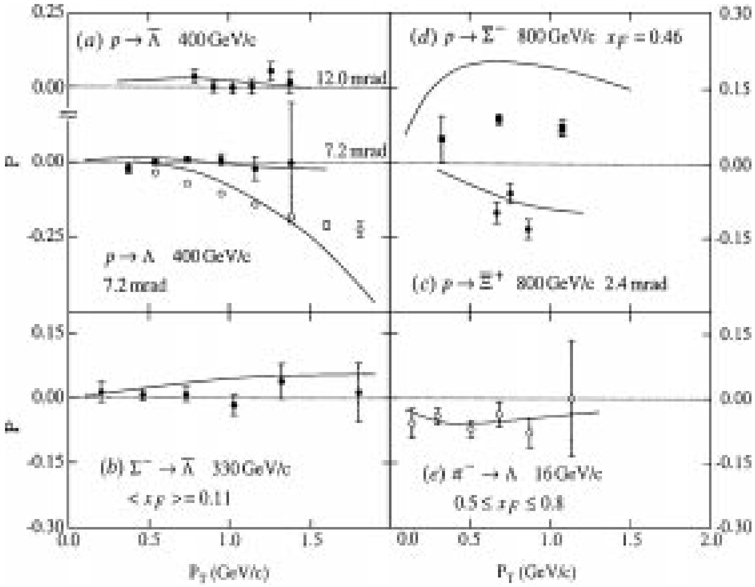

Figure 1. The hyperon spin polarizations as a function of P_T in the kinematical regions indicated. The observed data are taken from the works quoted in [14] and shown by the open symbols for the hyperons and by the solid symbols for the anti-hyperons. The solid curves for the anti-hyperons show the results obtained by the QRC process with the present primary ud-quark mechanism, and for the Λ polarizations in (a) and (e) are obtained by the standard QRC process.

In fact the measurements [10, 11] give results essentially consistent with zero for these no-valence quark cases, as shown in figures 1a and b for $\bar{\Lambda}$. We then had a good understanding that existence of a leading parton plays an essential role in the spin polarizations until two anomalous cases were discovered experimentally. One is the $\bar{\Xi}^+$ polarization [12] shown in figure 1c which is found to have almost the same polarization as that of Ξ^- (not shown here) and the other is $\bar{\Sigma}^-$ [13] shown in figure 1d with the same sign but less magnitude compared to Σ^+. We call this case as the *first puzzle* and we have reported our successful understanding for the puzzle [14]. Here we will shortly show essence of the result.

There exists another anomalous spin observable. The measurements [15] of analyzing power A_N and spin depolarization D_{NN} in $\vec{p}\,p \to \Lambda X$ reactions, where $\vec{p}$ presents incident protons with spin perpendicularly polarized in the scattering plane, show apparent non-zero values in the kinematical region above $x_F = 0.5$, contrary to the prediction of zero by the DM model with SU(6) baryon wave functions. Namely in the model, ud diparton with spin $S = 0$ from the projectile, and s parton from a created pair form Λ, but the initial spin carrier, u parton in the proton, does not participate in the Λ formation. Therefore Λ has no way to know whether or not the incident proton is spin polarized, and consequently A_N and D_{NN} become zero. Contrary to this prediction, the experiments show finite values to these spin observables [15], therefore we call it the *second puzzle*. To solve the puzzle, here we will propose a new spin transfer mechanism and show the process is quite promising to provide finite values of the A_N and D_{NN} in hyperon productions.

Recently, a measurement of the spin depolarization D_{NN} of an exclusive collision at 3.67 GeV$/c$ has been reported [16]. Natural extension of the diagram to be proposed for interpretation of the second puzzle predicts D_{NN} with positive sign in contrast to observation with negative sign. This new difficulty is referred to as the *third puzzle* in this article and we will discuss a possible mechanism by noting requirement of parity conservation.

2. The first puzzle: Extension of the standard QRC model

Multiplicity distributions of the products in pp, pA and AA collisions at high energies are well-known to be dominated by π and other light mesons made of ud quarks and antiquarks [17] produced primarily or secondarily. This is understood as due to the Schwinger mechanism for the quark pair creation, which is extremely sensitive to the quark mass. This fact indicates that many of the mesons with velocity as high as the incident hadrons are produced and hence may suggest a mechanism according to which constituent ud quarks and antiquarks of the mesons, hereafter referred to as *primary ud-quark*, participate as leading partons. They recombine with a successively produced parton of a created pair to make final hyperons. More generally, it is not necessary for π and other light mesons to be produced, but any mechanisms like the tube model and the string model are conceivable, in which light quarks and antiquarks are produced in the primary interaction [18]. The essential requirement is that those primary ud and anti-ud partons move with such high enough velocity compared with that of the picked up partons and that those particles are regarded as valence partons. This requirement is a consequence of the DM model as explained in the Introduction; the model requires valence parton (s) with large velocity (carrying up-spin) and sea parton (s) with small velocity (down-spin).

Accepting this extended mechanism we calculate the spin polarizations of outgoing hadrons by assuming the pion as incident particle. For the momentum distribution functions of the valence and the created partons, we use those of the pion [19].

The results of the calculation are shown by the solid curves and compared with the observed data in figure 1. The calculated $p \to \bar{\Lambda}$ polarizations for the two different kinematical regions are shown in (a). They are as small as the observations and much smaller than the $\pi^- \to \Lambda$ result shown in (e) which predicts quite well the observed data. We are careful to say 'consistent with zero' for the $\Sigma^- \to \bar{\Lambda}$ as seen in (b), so that altogether the further confusion pointed out above for the p and $\Sigma^- \to \bar{\Lambda}$ and the $\pi^- \to \Lambda$ is cleared up. The Λ polarization is shown in (a) for comparison. These small $\bar{\Lambda}$ polarizations are found to be caused in those kinematical regions by a large cancellation between the scalar and vector diquark contributions in association with the Λ wave function in SU(6) symmetry. The $\bar{\Xi}^+$ calculation (c) reasonably well reproduces the measurements and the $\bar{\Sigma}^-$ (d) gives the observed shape of the P_T distributions with the correct sign but too large magnitude by a factor two.

The present mechanism predicts various relations among the hyperon polarizations. First, there should be the relations; $P(p \to \bar{\Lambda}) = P(\pi^- \to \bar{\Lambda}) = P(\pi^- \to \Lambda)$. This relation indicates large polarizations for $p \to \bar{\Lambda}$ in the kinematical x_F region indicated in (e); $x_F = 0.5 - 0.8$. Note that the kinematics in the $\bar{\Lambda}$ in (a) and (b) corresponds roughly to $x_F = 0.1 - 0.3$. Second, the other prediction is $P(p \to \bar{\Xi}^0) = P(p \to \bar{\Xi}^+)$,

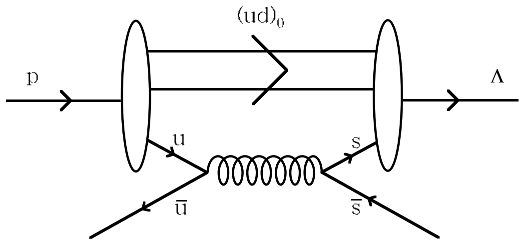

Figure 2. The diagram for a production of Λ from pp collision through $u\bar{u}$ annihilation and $s\bar{s}$ creation.

therefore, $= P(p \to \Xi^-)$ as discussed in (c). A further prediction is the same polarizations of $\bar{\Sigma}^+$ and $\bar{\Sigma}^0$ as that of $\bar{\Sigma}^-$ which is shown in (d). It is very interesting to test these relationships by measurements in order to confirm further the present mechanism.

3. The second puzzle: How to transfer spin information

As for the finite values of A_N and D_{NN} in the $\vec{p}\,p \to \Lambda X$ reaction [15], the question is to find a mechanism to transfer the initial spin direction of incident proton to the outgoing Λ. This may be possible in the framework of the QRC model by considering an annihilation and creation mechanism, as shown in figure 2, where the initial valence u quark, which carries the proton's spin information, annihilates with $\bar{u}$ in the target proton and then $s\bar{s}$ pair is created through the gluon propagation, and the s quark recombines with ud scalar diquark to form Λ. From the Clebsh–Gordon coefficients, we can estimate that the s quark has spin up with probability of 75% and spin down with that of 25%. Suppose the u quark with spin up annihilates with the $\bar{u}$ quark with spin up. Then intermediate gluon carries spin up and hence the created s and $\bar{s}$ quarks carry spin up, therefore the Λ particle with spin up is produced. On the other hand, if the u quark has spin down, the intermediate gluon carries zero spin direction and the s and $\bar{s}$ quarks do not have preferred spin directions, therefore for this case the initial spin information cannot be transferred to the produced Λ particle. In this way we can transfer spin information to s quark to form Λ particle.

However, this process should not be all. The standard QRC process also participates to Λ production. Since we do not know amount of the two contributions in kinematical region of interest, we write the probability of creating spin up s quark as $(1+\gamma)/2$ and spin down s quark as $(1-\gamma)/2$, for the case of the incident proton with spin up. Then using the DM empirical rule and the parameter ϵ, $\vec{p} \to \Lambda$ production cross-sections can be expressed as

$$\sigma_{\uparrow\uparrow(\uparrow\downarrow)} = \frac{1 \pm \gamma}{2}(1 \mp \epsilon), \quad \sigma_{\downarrow\uparrow(\downarrow\downarrow)} = \frac{1 \mp \gamma}{2}(1 \mp \epsilon), \tag{1}$$

where e.g. $\uparrow\downarrow$ means proton (u) spin up and $\Lambda(s)$ spin down, respectively. Using these cross sections, we obtain the relations,

$$P = -\epsilon, \quad D_{NN} = \gamma, \quad A_N = -\gamma\epsilon = D_{NN} P. \tag{2}$$

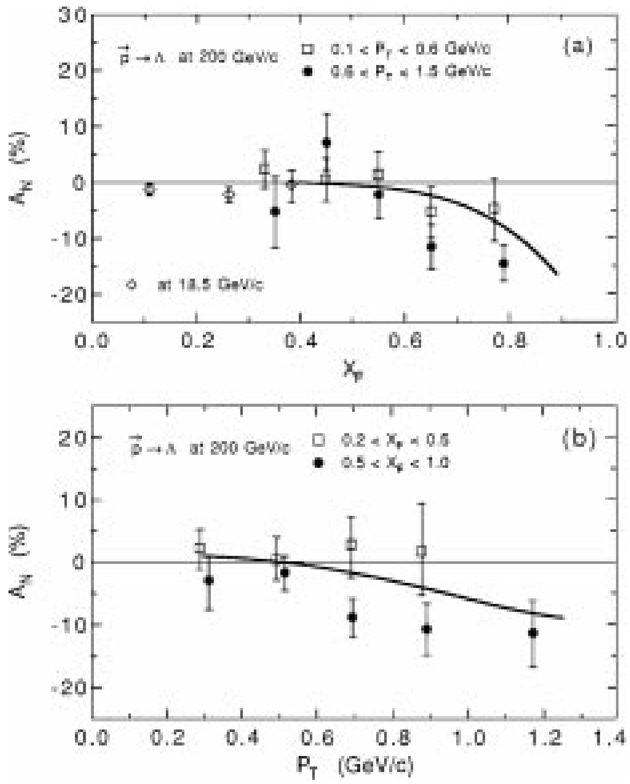

Figure 3. The A_N of $\vec{p}\,p \to \Lambda X$ reaction. The solid curves are obtained using the calculated P and the observed D_{NN}, according to $A_N = D_{NN}P$ found in the present spin transfer process, for the kinematical parameters $P_T = 1$ GeV$/c$ in (**a**) and $x_F = 0.2-1.0$ in (**b**). The experimental data are taken from the works quoted in the text.

We are not able to predict the spin depolarizing parameter γ which needs information on the dynamics of the quark-antiquark annihilation and creation through gluon exchange, but we can calculate the spin polarization $P(x_F, P_T)$ from our QRC model. Therefore in this article, we test the consistency of the last relation in eq. (2), since we find γ to be just the spin depolarization itself for which measurements exist [15]. Using our calculated polarization $P(x_F, P_T)$ and accepting the observed values for $D_{NN}(x_F, P_T)$, we obtain A_N and compare it with the measurements. In figure 3, the results are shown by the solid curves. The kinematical parameters $P_T = 1$ GeV/c for (a) and $x_F = 0.2-1.0$ for (b) were used in the $P(x_F, P_T)$ calculation, therefore the obtained results should be rather compared with the solid circles in the both figures 3a and b; the signs and slopes obtained (in (a)) and estimated (in (b)) by the present calculation are consistent with the measurements and this fact indicates the present u annihilation and s creation mechanism being quite promising to solve the second puzzle.

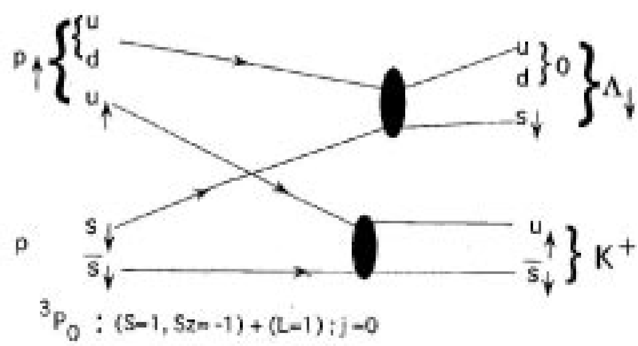

Figure 4. The leading order diagram based on the originally used Λ spin polarization in the inclusive $\vec{p}\,p \rightarrow \Lambda X$ collision and extended to the exclusive $\vec{p}\,p \rightarrow \Lambda K^{+}p$ collision.

4. The third puzzle: The diagram for the exclusive $\Lambda K^{+}p$ production

Recently, D_{NN} of an exclusive $\vec{p}\,p \rightarrow \Lambda K^{+}p$ collision at 3.67 GeV/c has been observed [15]. The result shows negative sign, that is different from sign of the previous inclusive Λ production case. Our annihilation and creation diagram figure 2 can be extended to the exclusive production to form K^{+} by merging $\bar{s}$ having spin-up with the counter parton u of the created $u\bar{u}$ pair having spin-down. This, however, produces Λ with spin-up, therefore the calculated spin depolarization D_{NN} could have positive sign in contrast to the negative sign observed if the spin flip cross section is small.

Therefore something may be lack in our interpretation of the exclusive production mechanism mentioned above. Perhaps, lack is consideration of parity. In fact, it is apparent that the simply extended diagram from figure 2 does not conserve parity. Hence we consider P-wave contribution, namely we create $u\bar{u}$ pair with ${}^{3}P_{0}$ configuration. Then we can easily show that the new diagram is possible to produce Λ with spin-down and possibly D_{NN} with negative sign.

However, there exists a more fundamental (leading order) graph which was originally used in the Λ inclusive production. We extend this diagram to the exclusive $pp \rightarrow K^{+}\Lambda p$ production with the parity conservation condition. One of the possible four new graphs is shown in figure 4 and we find that spin direction of the produced Λ is down, so that we may obtain negative value for the spin depolarization for this graph.

We similarly estimated the spin dependent cross sections as described in §3 but by introducing the two parameters, λ and κ with positive sign, characterizing the DM empirical rule since now we concern the two hadrons, Λ and K^{+}, production case. Using these cross sections, we obtained the following relations corresponding to eq. (2)

$$P = -\lambda, \quad A_{N} = \kappa, \quad D_{NN} = -\lambda\kappa = PA_{N}. \tag{3}$$

This predicts a negative sign for D_{NN} of the present exclusive production, which is consistent with the observed result.

5. Summary

To resolve the anomalous spin observables found in the anti-hyperon spin polarizations, we have proposed new mechanism: the primary ud quark mechanism. We have applied our microscopic quark recombination model to the spin polarizations and shown that the calculations with the present mechanism predict large polarizations where large polarizations are observed and vice versa, so that the first puzzle clearly disappears.

For the second puzzle of the unexpected analysing power and spin depolarization in the $\vec{p}\, p \to \Lambda X$ reaction, we have indicated a possible spin transfer mechanism (u annihilation and s creation) in the intermediate stage, which provides finite value for these observables. A simple relationship among the three spin observables (P, A_N, D_{NN}) has been found and we have confirmed that the relation provides the result consistent with the measurements. Thus the second problem has also been clearly solved. The spin depolarizing parameter γ, and therefore the sea quark polarizing dynamics through the u annihilation and s creation is left for future study. It is a useful finding that spin depolarization provides a direct information for this q–q interaction study.

For the third difficulty of difference in sign between the two D_{NN}'s of Λ observed in the inclusive $\vec{p}\, p \to \Lambda X$ and the exclusive $\vec{p}\, p \to \Lambda K^+ p$ collisions, we have proposed a possible mechanism with satisfying parity conservation. This mechanism is an extension of the the diagram originally used and established for the spin polarization calculation of $pp \to \Lambda X$ inclusive collision. We are now calculating D_{NN} for the exclusive $\vec{p}\, p \to \Lambda K^+ p$ by using this mechanism.

Through all these systematic studies of spin transfer mechanisms both in the normal and anomalous hadron production processes with our basic microscopic QRC model, we like to contribute to precise understanding of nucleon structure, the QCD spin physics and the confinement interactions.

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