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POLARIZATION EFFECTS IN HADRON FRAGMENTATION

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1. The fact of a large polarization of hyperons produced in the fragmentation region of a primary hadron ($a \to Y$) has been established in a number of experiments (see, e.g., ref. [1]). The polarization achieves 20-30% at transverse momenta $p_T \sim$ ~ 1 GeV/c and is practically independent of energy. It is also known that the hyperon polarizations measured along the normal to the reaction plane $\vec{n} = [\vec{p}_a \times \vec{p}_Y]$ approximately satisfy the following relations: $P_{\Sigma^+} = -P_\Lambda = -P_{\Xi^-} = -P_{\Xi^0} > 0$ in proton fragmentation and $P_\Lambda > 0$ in the reaction $\bar{K}^- \xrightarrow{N} \Lambda$. $\bar{\Lambda}$-polarization in these processes is practically equal to zero. A large polarization, not vanishing with increasing energy, may point to a simple polarization mechanism at the level of hadron constituents. Thus in ref. [2] these data have been explained in terms of the recombination parton model (taking into account SU(6)-symmetry of hadron wave functions) as a result of constituent polarization appearing due to their acceleration or deceleration in the confining field (see also ref. [3]). However, some predictions of ref. [2] contradict, or are in bad agreement with the results of recent experiments [1]. These are approximately equal Σ^-- and Σ^+-polarizations in the proton fragmentation, a large Ξ^--polarization in the reaction $K^- \xrightarrow{N} \Xi^-$ ($P_{\Xi^-} \simeq 50\%$ at $p_T = 0.5$ GeV/c) and practically zero Λ-polarization in the reactions π, K^+, $\gamma \xrightarrow{N} \Lambda$. It will be shown that a specification of the model allows one to explain, at least qualitatively, these data as well. The model predictions for hadron polarization and polarization asymmetry in the fragmentation of polarized baryons and vector meson spin alignment in hadronic reactions are also discussed.

2. We briefly summarize the results of ref. [2]. Consider the fragmentation $p \to \Lambda$ at first. A main contribution to the cross section of this process comes from the recombination of a fast valence diquark $(ud)_0$ having zero spin and isospin, with a slow sea s-quark which is accelerated in the confining field by force $\vec{F}$ along the direction of primary proton momentum and it obtains negative polarization $-\epsilon = P_\Lambda$. In ref. [2] this polarization is connected with a contribution of the spin-orbit interaction to the constituent Hamiltonian. In the case of scalar confining field this contribution $H = \vec{s}\vec{\omega}_T$ is determined by the Thomas procession vector $\vec{\omega}_T \simeq [\vec{F} \times \vec{\beta}] / m$ ($\vec{\beta}$ and m are the constituent velocity and mass) which, at large enough p_T, is directed parallel or antiparallel to the normal $\vec{n}$ of the reaction plane depending on that whether the constituent is accelerated or decelerated. Thus the minimal energy configuration in the fragmentation $p \to \Lambda$ is achieved provided that the

s-quark (Λ-hyperon) spin is directed along $-\vec{n}$ in agreement with experiment. In the reaction $K^- \xrightarrow{N} \Lambda$ the fast valence s-quark from the K^--meson is now decelerated and enters into the Λ-hyperon state with positive polarization ϵ_V. Experimentally, the positive Λ-polarization is indeed seen and $\epsilon_V \geq \epsilon$. In the fragmentation $p \longrightarrow \Sigma^+$ the dominant contribution is due to the recombination of slow sea s-quark with fast valence spin-1 diquark $(uu)_1$. The decelerated diquark gets positive polarization $\frac{2}{3}\delta_V$ so that the Σ^+-polarization is also positive: $P_{\Sigma^+} = \frac{1}{3}\epsilon + \frac{2}{3}\delta_V$. Experiment requires $\delta_V \simeq \epsilon$. It is assumed that the diquark spin density matrix can be described with the help of only one parameter δ_V, i.e., $\rho_{oo} = \frac{1}{3}, \rho_{\pm 1 \pm 1} = \frac{1}{3}(1 \pm \delta_V)$. In the model considered, such an assumption can be justified provided that the diquark spin alignment is not large. In the fragmentation $p \longrightarrow \Sigma^o$ the $(uu)_1$-diquark is replaced by the valence $(ud)_1$-diquark, and the model predicts $P_{\Sigma^o} = P_{\Sigma^+}$ in agreement with the experimental indication of a positive Σ^o-polarization[1]. The recombination of a proton valence quark with two sea quarks makes a main contribution to the $p \longrightarrow \Xi, \Sigma^-$ fragmentation cross sections. In ref.[2] the two sea quarks are assumed to form a sea diquark which is accelerated in the confining field. The sea spin-1 diquark thus gets negative polarization $-\frac{2}{3}\delta$. We then have* $P_{\Xi} = -\frac{1}{3}\epsilon_V - \frac{2}{3}\delta$ and $P_{\Sigma^-} = \frac{2}{3}\epsilon_V - \frac{1}{6}\delta$. Analogously the model predicts $P_{\Xi}(K^- \rightarrow \Xi) = P_{\Sigma^-}(p \rightarrow \Sigma^-)$ provided that the quark polarization is independent of its mass. Assuming $\epsilon_V \simeq \epsilon \simeq \delta \simeq \delta_V$, like in ref.[2], these predictions agree with experimental data on the Ξ-polarization in the proton fragmentation; however, they presumably underestimate the hyperon polarization in the reactions $p \rightarrow \Sigma^-$ and $K^- \xrightarrow{N} \Xi^-$. Besides, the model predicts negative Λ-polarization $P_\Lambda = -\frac{1}{2}\delta$ in the reactions π, K^+, $\gamma \xrightarrow{N} \Lambda$ instead of practically zero Λ-polarization seen experimentally (though the experimental errors are quite large).

3. The discrepancies mentioned above can be, at least in part, removed taking $\epsilon_V > \epsilon$ into account. An agreement of the model with experiment is further improved if we assume that the production of spin-1 sea diquarks, which are heavier than the scalar diquark $/m_\Delta > m_N/$, is damped by a factor of $\lambda = \frac{1}{3}(qq)_1/(qq)_o < 1$. For $\lambda \ll 1$ the Λ-polarization in the reactions π, K^+, $\gamma \rightarrow \Lambda$ turns out to be positive $P_\Lambda = \epsilon_V$ so that choosing appropriately the parameter λ ($\lambda \simeq \frac{1}{3}$ at $\epsilon_V \simeq \delta$), we can achieve $P_\Lambda = 0$. Besides, for the reactions $p \rightarrow \Sigma^-$ and $K^- \xrightarrow{N} \Xi^-$, we then have $P_{\Sigma^-} = P_{\Xi^-} \simeq 0.8\epsilon_V$. It should be noted, however, that the assumption[2] of the formation of a slow sea diquark is not always justified. To see this, we consider the fragmentation process in terms of the dual unitarization scheme[4] taking into account the Y-shaped form of a baryon[5]. In this scheme, a main contribution to particle production is due to the division of colour flux tubes-strings stretched between the constituents with opposite colour charges, e.g., $\bar{q} - q$ and $q - Jqq$ in meson-baryon interactions (J is the string junction - a diquark $J\!\!<^{q}_{q}$ constituent). When a baryon is produced containing less than two valence quarks from the primary baryon, sea quarks should be also created by dividing a "short" string between the string junction and a valence quark in the diquark. A new diquark can be formed in this process not only from sea quarks but also from a valence and a sea quark. Therefore in the fragmentation $p \rightarrow \Xi$ we should take into account the recombination of a decelerated ds- or us-diquark with a slow sea s-quark which yields $P_{\Xi} \simeq -0.8\epsilon$ at $\lambda \simeq \frac{1}{3}$. In the fragmentation $p \rightarrow \Sigma^-$ the recombination of dd-diquark with sea s-quark (we neglect the formation of ds-diquark since the s-quark creation due to the division of a "short" string is damped as compared to the creation of light d-quark) gives $P_{\Sigma^-} = P_{\Sigma^+} \simeq \epsilon$. It is seen that the polarizations connected with these contributions also agree with experiment.

On the other hand, for the reactions with diquark formation in the recombination process it is reasonable to consider the situation when quarks are polarized independently (see also ref.[3]). We then have $P_{\Sigma^-} = \frac{2}{3}(\epsilon_V - \epsilon') + \frac{1}{3}\epsilon$ and $P_{\Xi} = -\frac{2}{3}(\epsilon + \epsilon') - \frac{1}{3}\epsilon_V$ in the proton fragmentation, where $-\epsilon'$ is the polarization of the sea quark produced by the division of a "short" string. Since this quark has smaller $\langle p_T \rangle$ than the ordinary sea quark[3] (and also due to the circumstance that the division of a "short" string can occur both before and behind the string junction, i.e., the sea quark can be both accelerated and decelerated), we expect $|\epsilon'| \ll \epsilon$. Thus, at $\epsilon_V \simeq \epsilon$ we have $P_{\Sigma^-} \simeq -P_{\Xi} \simeq \epsilon$ in accordance with which is experimentally observed. In the reaction $K^- \xrightarrow{N} \Xi^-$ at not too large energies the recombining d-quark is predominantly a valence target quark (when accelerated, it gets polarization $-\epsilon_V$) so that $P_{\Xi^-} = \frac{2}{3}(\epsilon_V - \epsilon') + \frac{1}{3}\epsilon_V \simeq \epsilon_V$ as required by experiment. For the processes $K^- \rightarrow \Lambda$ and π, K^+, $\gamma \rightarrow \Lambda$ we get, in agreement with experiment, $P_\Lambda = \epsilon_V > 0$ and $P_\Lambda = -\epsilon' \simeq 0$, respec-

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* In ref.[2] $P_{\Sigma^-} = P_{\Xi}$ has been erroneously obtained.

tively. In the first reaction the valence s-quark from the K^--meson comes into the Λ-hyperon state with positive polarization ϵ_V, while in the other reactions the s-quark is produced by the division of a "short" string and is practically not polarized.

4. For vector meson production with large enough p_T the considered model predicts a large (> 1/3) probability ρ^T_{oo} of the zero spin projection on the normal to the reaction plane (the recombining quark and antiquark are polarized in the approximately opposite directions), i.e., $\rho^T_{oo} = (1+\epsilon^2)/(3-\epsilon^2) \geq 1/3$ (here and later on we put $\epsilon_V = \epsilon$ for simplicity). This prediction is found [6] to be in agreement with experiment.

The model can be also applied to describe the fragmentation of polarized hadrons. We consider the polarization asymmetry $A_c = \frac{1}{P_o}(N_+ - N_-)/(N_+ + N_-)$ in the fragmentation $p \to c$ (see also ref. [6]). Here $N_{+(-)}$ is the c-particle yield in the case when the proton polarization vector $\vec{P}_o$ is directed parallel (antiparallel) to the normal $\vec{n}$ to the reaction plane, $\vec{n} = [\vec{p}_p \times \vec{p}_c]$. Assuming the constituent interaction with the confining field is an elastic one*, the model predicts $A_{\pi^+(K^+)} = -2A_{\pi^-} = 4A_{\pi^o} = \frac{4}{3}\epsilon/(1+\epsilon^2) > 0$. This is in qualitative agreement with the experimental data at $p_T \sim 1$ GeV/c [7,8]. Note, however, that the restriction $|A_{\pi^o}| \leq 1/6$ following from the model is in contradiction with an indication of a large ($\gtrsim$0.5) polarization asymmetry of π^os in pp interactions at 24 GeV/c in the region x = 0–0.1 and $p_T >$ 2 GeV/c [8]. We can try to explain this result assuming that at large p_T the proton predominantly fragmentizes into a valence u-quark and a scalar ud-diquark, i.e., mostly the u-quark carrying the proton spin comes into the produced hadron**. In this case $A_{\pi^o} = A_{\pi^+} = 2\epsilon/(1+\epsilon^2) \leq 1$. At small $|x|$, however, the model yields $A_\pi < 1/2$ and $A_\pi \to 0$ with increasing energy. We note further that the polarization asymmetry data presumably exclude the spontaneous radiation mechanism of quark polarization in the confining field suggested in ref. [9] to explain the polarization effects (quarks become polarized due to different probabilities of spin flip radiation transitions $1/2 \to -1/2$ and $-1/2 \to 1/2$). This mechanism predicts a vanishing polarization asymmetry at large enough p_T since the quarks obtain polarization which is independent of the primary hadron polarization.

A study of hadron polarization in the fragmentation of polarized baryons can serve as a sensitive, though difficult enough, test of the model considered, e.g., for the reaction $p \to \Sigma^{+,o}$ the model predicts $P_\Sigma = (\frac{2}{3}P_o + \frac{2}{3}\delta_V + \frac{1}{3}\epsilon)/(1 + \frac{2}{3}P_o(\delta_V + \epsilon))$, where P_o is the primary proton polarization along the normal to the reaction plane. Thus, at $|P_o| \sim 1$ the Σ-hyperon obtains approximately 2/3 of the proton polarization: $P_\Sigma \approx \frac{2}{3}P_o + \frac{1}{9}\epsilon$. At the same time the polarization mechanism, due to spontaneous radiation, yields $P_\Sigma = \frac{2}{3}P_o$ at small p_T (probability of the quark spin flip is small) while $P_\Sigma = P_\Sigma(P_o = 0) = \frac{2}{3}\delta_V + \frac{1}{3}\epsilon$ at large enough p_T.

The constituent spin flip transition amplitudes are neglected in ref. [2]. This can be justified provided constituents interact (elastically) with the external field only (though, in principle, the diquark spin flip transitions $1 \to -1$ are possible in this case). In general, if constituents are polarized in an elastic process*, the corrections due to these amplitudes weaken the polarization effects. If we further allow transitions between scalar and vector diquarks, the model predictions for some fragmentation cross sections can essentially change. For example, the model predicts the ratios 9:4:1 for direct yields of Λ-, Σ^+ and Σ^o-hyperons in the proton fragmentation (a large Λ-hyperon yield is due to a large weight of $(ud)_o$-diquark in the SU(6) proton wave function)**. The difference between Λ- and Σ^o-yields becomes smaller if the transitions $(ud)_o \to (ud)_1$ take place.

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* In this case the constituents are presumably polarized due to transitions connected with a tunneling process (for sea constituents) [3] or with the rearrangement of the colour flux tubes (for valence constituents). A further interaction (elastic) of the constituents with the confining field in the recombination process leads only to a precision of the spin around the normal to the production plane but not to the polarization [3]. The polarization in the recombination stage is, however, possible in an inelastic process, e.g., due to spontaneous radiation.

** This assumption is in accordance with the scalar ud-diquark being a more strongly bound system than the vector diquark ($m_N < m_\Delta$) and also with the fact of a harder momentum distribution of u-quarks in the proton as compared with the d-quark one.

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* A direct check of this assumption is possible in the fragmentation $\Lambda \to \Lambda$. According to the Wolfenstein theorem, $P_\Lambda = A_\Lambda$ is required.

** This relation is violated by the recombination processes with initial diquark splitting. Their contribution increases with decreasing $|x|$, e.g., in the fragmentation $p \to \Sigma^+$, it is quite essential even at $x \approx 0.5$ $(\sigma(\Sigma^-))\sigma(\Sigma^+) \approx 1/3$ at $x = 0.5$ [10]).

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Ледницки Р. E2-84-12

Поляризационные эффекты в процессах адронной фрагментации

Обсуждаются предсказания рекомбинационной кварковой модели с учетом спин-орбитального взаимодействия для поляризации /выстроенности спина/ и поляризационной асимметрии адронов в процессах адронной фрагментации. Показано, что эти предсказания, по крайней мере, качественно согласуются с экспериментальными данными. В рамках данной модели обсуждаются также различные поляризационные механизмы и возможность их проверки.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Polarization Effects in Hadron Fragmentation

Hadron polarization (spin alignment) and polarization asymmetry are discussed in terms of the quark recombination model with the spin-orbit interaction taken into account. It is shown that predictions of this model are at least in qualitative agreement with experimental data. Various polarization mechanisms in terms of this model and the possibility of their checking are also discussed.

The investigation has been performed at the Laboratory of High Energies, JINR.

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