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SPIN EFFECTS AND ROLE OF CONSTITUENT QUARK SIZE

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The nonperturbative mechanism for spin effects in inclusive production based on the constituent quark model is considered. The main role belongs to the orbital angular momentum and the polarization of the $\bar{q}q$-pairs in the internal structure of the constituent quarks.

Исследуется механизм спиновых эффектов в инклюзивном образовании, основанном на модели конституентного кварка. Основная роль принадлежит орбитальному угловому моменту и поляризации пары $\bar{q}q$ во внутренней структуре конституентных кварков.

It is a well-known fact that spin observables demonstrate rather complicated behaviour and it somehow is related to a scarcity of the experimental data in the field. However, it seems very important to find some general trends in the data even under such strained circumstances. One among the more or less stable patterns is the momentum transfer dependence of various spin observables in inclusive production. To be specific we will concentrate on a particular problem of Λ polarization. Experimentally, the situation is stable and clear. Λ polarization is negative and energy-independent. It grows linearly with x_F for $p_\perp > 0.8$ GeV/c, and for large values of the momentum transfer ($0.8 < p_\perp < 3.5$ GeV/c) it is $p_\perp$-independent [1,2]. It is remarkable that both parameters A_N and D_{NN} show $p_\perp$ dependence similar to polarization [3].

In perturbative QCD a straightforward collinear factorization leads to very small values of P_Λ [4, 5]. pQCD modifications and in particular account for higher twists results in the dependence $P_\Lambda \sim 1/p_\perp$ [6–8]. This behavior still does not correspond to the experimental trends. Account for $k_\perp$ effects when the source of polarization is shifted into the polarizing fragmentation functions also leads to falling $P_\Lambda \sim k_\perp/p_\perp$ at large $p_\perp$ values [9]. Potentially Λ polarization could become even a more serious problem than the nucleon spin problem. And in any case both the problems are interrelated.

The essential point here is that the vacuum at short distances is taken to be a perturbative one. However, polarization dynamics could have its roots hidden in the genuine nonperturbative sector of QCD. The models exploiting confinement and the chiral symmetry breaking have been proposed. Our model considerations [10] are based on the effective Lagrangian approach which in

addition to the four-fermion interactions of the original NJL model includes the six-fermion $U(1)_A$-breaking term.

Chiral symmetry breaking generates quark masses:

$$m_U = m_u - 2g_4\langle 0|\bar{u}u|0\rangle - 2g_6\langle 0|\bar{d}d|0\rangle\langle 0|\bar{s}s|0\rangle.$$

In this approach massive quarks appear as quasiparticles, i.e., current quarks surrounded by a cloud of quark–antiquark pairs of different flavors. For example, for the U quark the ratio

$$\langle U|\bar{s}s|U\rangle/\langle U|\bar{u}u + \bar{d}d + \bar{s}s|U\rangle$$

is estimated as $0.1-0.5$. The scale of spontaneous chiral symmetry breaking is

$$\Lambda \simeq 4\pi f_\pi \simeq 1 \text{ GeV}/c$$

and provides the momentum cutoff which determines a transition to the partonic picture. We consider nonperturbative hadron as consisting of constituent quarks located in the central part of the hadron and embedded into a quark condensate.

Respectively, spin of the constituent quark is given by the following «spin balance equation»:

$$J_U = 1/2 = S_{u_v} + S_{\{\bar{q}q\}} + L_{\{\bar{q}q\}} = 1/2 + S_{\{\bar{q}q\}} + L_{\{\bar{q}q\}}, \qquad (1)$$

where $L_{\{\bar{q}q\}}$ is the orbital angular momentum of quark–antiquark pairs in the structure of the constituent quark. Its value can be estimated [10] with the use of the polarized DIS data:

$$L_{\{\bar{q}q\}} \simeq 0.4. \qquad (2)$$

This means that the cloud quarks rotate coherently and significant part of the constituent quark spin is to be associated with the orbital angular momentum. In the model just this orbital motion of quark matter is the origin of asymmetries in inclusive processes. It is to be noted that the only effective degrees of freedom here are quasiparticles. The gluon degrees of freedom are overintegrated, and the six-fermion operator in the NJL Lagrangian simulates the effect of the gluon operator $(\alpha_s/2\pi)G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$ in QCD. It is also important to note the exact compensation between the spins of $\bar{q}q$ pairs and their orbital momenta:

$$L_{\{\bar{q}q\}} = -S_{\{\bar{q}q\}}, \qquad (3)$$

which follows from Eq. (1).

Assumed picture of hadrons implies that overlapping and interaction of peripheral clouds and condensate excitation occur at the first stage of the collision. As a result massive virtual quarks appear in the overlapping region and some

mean field is generated. Inclusive production of hyperon results from the two mechanisms: recombination of constituent quark with virtual massive strange quark (soft interactions) or from the constituent quark scattering in the mean field, its excitation and appearance of a strange quark as a result of decay of the parent constituent quark. The second mechanism is determined by interactions at the distances smaller than the constituent quark radius ($r < R_Q \sim 1/\Lambda_\chi$) and is associated with hard interactions. Thus, we adopt a two-component picture of hadron (hyperon) production which incorporates interactions at long and short distances and it is the short distance dynamics which leads to production of polarized Λ's.

Polarization of a strange quark results from the multiple scattering of parent constituent quark Q in the mean field where it gets polarized

$$\mathcal{P}_Q \propto -I\frac{m_Q g^2}{\sqrt{s}} \tag{4}$$

and the polarization is nearly constant in the model since $m_Q \sim m_h/3$ and $I \sim \sqrt{s}$. The second crucial point is correlation between s-quark polarization and polarization of the parent quark Q. Indeed, the total orbital momentum of $\bar{q}q$ pairs in the constituent quark which has polarization $\mathcal{P}_Q(x)$ is

$$L_{\{\bar{q}q\}}^{\mathcal{P}_Q(x)} = \mathcal{P}_Q(x)L_{\{\bar{q}q\}}, \tag{5}$$

where the value $L_{\{\bar{q}q\}}$ on the right-hand side enters Eq. (1) written for the constituent quark with polarization $+1$. On the basis of Eq. (3) we suppose that there is a compensation between spin and orbital momentum of strange quarks inside the constituent quark

$$L_{s/Q} = -J_{s/Q} = \alpha\mathcal{P}_Q(x)L_{\{\bar{q}q\}}, \tag{6}$$

where the parameter α determines the fraction of orbital momentum due to the strange quarks. Equation (6) is quite similar to the conclusion made in the framework of the Lund model but has a different dynamical origin rooted in the mechanism of the spontaneous chiral symmetry breaking.

Final expression for the polarization is

$$P(s, x, p_\perp) = \sin\left[\alpha\mathcal{P}_Q(x)L_{\{\bar{q}q\}}\right]\frac{R(s, x, p_\perp)}{1 + R(s, x, p_\perp)}. \tag{7}$$

The function R is the cross-section ratio of hard and soft processes. At $p_\perp > \Lambda_\chi$ the function $R(s, x, p_\perp) \gg 1$ and the polarization saturates

$$P(s, x, p_\perp) = \sin\left[\alpha\mathcal{P}_Q(x)L_{\{\bar{q}q\}}\right]. \tag{8}$$

Characteristic $p_\perp$ dependence of Λ polarization follows from Eqs. (7) and (8): polarization is vanishing for $p_\perp < \Lambda_\chi$, it gets an increase in the region of $p_\perp \simeq \Lambda_\chi$ and polarization saturates and becomes $p_\perp$-independent (flat) for $p_\perp > \Lambda_\chi$. The respective scale is the scale of the spontaneous chiral symmetry breaking $\Lambda_\chi \simeq 1$ GeV/c. Such a behavior of polarization follows from the fact that constituent quarks themselves have slow (if at all) orbital motion and are in the S state, but interactions with $p_\perp > \Lambda_\chi$ resolve the internal structure of constituent quark and feel the presence of internal orbital momenta inside this constituent quark.
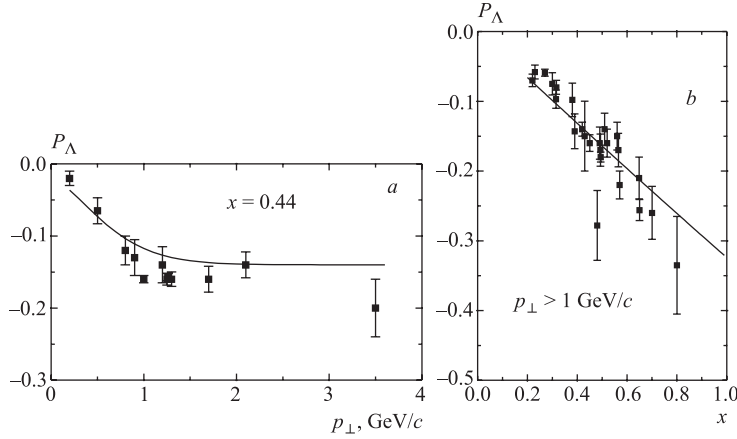
To describe the data quantitatively we have to introduce some parameterization. The function

$$R(s, x, p_\perp) = C(x) \exp\left(p_\perp/m\right)/(p_\perp^2 + \Lambda_\chi^2)^2 \qquad (9)$$

implies typical behavior of cross sections for hard and soft processes. The form

$$\mathcal{P}_Q(x) = \mathcal{P}_Q^{\max} x$$

is suggested by the ALEPH data [11]. The value of Eq. (2) alongside with $m = 0.2$ GeV and $\alpha = 0.8$ provides a rather good fit to the experimental data (see the figure).

Transverse momentum (*a*) and Feynman x (*b*) dependences of P_Λ

In the model the spin transfer parameter D_{NN} is positive since P_Λ has the same sign as $\mathcal{P}_Q$. The model also predicts similarity of $p_\perp$ dependences for the different spin observables. The respective features were clearly seen in E-704 experiment [3].

EXPERIMENTAL PROSPECTS

In this approach the short distance interaction with $p_\perp$, Λ_χ observes a coherent rotation of correlated $\bar{q}q$ pairs inside the constituent quark and not a gas of the free partons. The nonzero internal orbital momenta in the constituent quark means that there are significant multiparton correlations. The important point: what is the origin of this orbital angular momentum? The analogy with an anisotropic extension of the theory of superconductivity seems match well with the adopted picture for a constituent quark. An axis of anisotropy can be associated with the polarization vector of the valence quark located at the origin of the constituent quark.

It seems interesting to perform Λ-polarization measurements at RHIC. When two polarized nucleons are available, one could measure three-spin correlation parameters $(n, n, n, 0)$ and $(l, l, l, 0)$ in the processes

$$p_{\uparrow, \rightarrow} + p_{\uparrow, \rightarrow} = \Lambda_{\uparrow, \rightarrow} + X. \tag{10}$$

It would provide important data to study the mechanisms of hyperon polarization.

Experimentally observed persistence and constancy of Λ-hyperon polarization means that chiral symmetry is not restored in the region of energy and values of $p_\perp$ where experimental measurements were performed. Otherwise we would not have any constituent quarks and should expect a vanishing polarization of Λ. It is interesting to perform Λ-*polarization measurements at RHIC and the LHC. It would allow one to make a direct check of perturbative QCD and allow one to make a cross-check of the QCD background estimations based on perturbative calculations for the LHC*. On the basis of the above model we expect significant P_Λ at RHIC energies. On the base of the model, one expects zero polarization in the region where QGP has been formed, since chiral symmetry is restored and there is no room for quasiparticles such as constituent quarks. The absence or strong diminishing of transverse hyperon polarization can be used therefore as a signal of QGP formation in heavy-ion collisions. This prediction should also be valid for the models based on confinement, e.g., the Lund and Thomas precession model. In particular, the polarization of Λ in heavy-ion collisions in the model based on the Thomas precession was described, and nuclear effects were discussed as well. However, we do not expect a strong diminishing of the Λ polarization due to the nuclear effects: the available data show a weak A dependence and are not sensitive to the type of the target. Thus, we could use a vanishing polarization of Λ hyperons in heavy-ion collisions as a sole result of QGP formation provided the corresponding observable is nonzero in proton–proton collisions. The prediction based on this observation would be a decreasing behavior of polarization of Λ with the impact parameter in heavy-ion collisions in the region of energies and densities where QGP was produced: $P_\Lambda(b) \rightarrow 0$ at $b \rightarrow 0$, since the overlap is maximal at $b = 0$. The value of the

impact parameter can be controlled by the centrality in heavy-ion collisions. The experimental program should therefore include measurements of Λ polarization in *pp* interactions first, and then, if a significant polarization would be measured, the corresponding measurements could be a useful tool for the QGP detection. Such measurements seem to be experimentally feasible at RHIC and LHC provided it is supplemented with forward detectors.

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