Hyperon polarization in the constituent quark model

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We consider a nonperturbative mechanism for hyperon polarization in inclusive production at moderate transverse momenta. The main role belongs to the orbital angular momentum and the polarization of the strange quark-antiquark pairs in the internal structure of the constituent quarks. We consider a nucleon as a core consisting of the constituent quarks embedded into a quark condensate. The nonperturbative hadron structure is inspired by the results of the chiral quark models. [S0556-2821(97)02303-5]

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I. INTRODUCTION

One of the most persistently puzzling spin effects was observed in inclusive hyperon production under collisions of unpolarized hadron beams. A very significant polarization of Λ hyperons was discovered two decades ago [1]. Since then measurements in different processes have been performed [2] and a number of models have been proposed for a qualitative and quantitative description of these data [3]. Among them are the Lund model based on the classical string mechanism of strange quark pair production [4], models based on the spin-orbital interaction [5] and the multiple scattering of massive strange sea quarks in an effective external field [6], and also models for polarization of Λ in diffractive processes with account for proton states with additional $\overline{ss}$ pairs such as $|uud\overline{ss}\rangle$ [7,8]. It was proposed also to connect Λ polarization in the process $pp\to\Lambda X$ with the polarization in the process $\pi p\to\Lambda K$ [9] and use the triple-Regge approach [10].

The mechanism of gluon fusion in perturbative QCD as a source of strange quark polarization has been considered in [11] and the x and $p_\perp$ dependences of Λ polarization have been discussed.

Nonetheless, hyperon polarization phenomena are not completely understood in QCD and currently may be considered as a serious problem.

One could attempt to connect the spin structure of nucleons studied in deep-inelastic scattering with the polarization of Λ's observed in hadron production. As is widely known now, only part (less than one-third in fact) of the proton spin is due to the quark spins [12,13]. These results can be interpreted in the effective QCD approach ascribing a substantial part of hadron spin to the orbital angular momentum of quark matter. It is natural to guess that this orbital angular momentum might be revealed in the spin asymmetries in hadron production.

It is also evident from deep-inelastic scattering data [12–14] that strange quarks play an essential role in the proton structure and in the spin balance in particular. They are negatively polarized in a polarized nucleon, $\Delta s\simeq -0.1$. Polarization effects in hyperon production also demonstrate [2] that strange quarks produced in hadron interactions appear to be polarized.

In recent papers [15] we considered a possible origin of the asymmetry in pion and φ-meson production under the collision of a polarized proton beam with an unpolarized proton target and argued that the orbital angular momentum of partons inside the constituent quarks could lead to significant asymmetries in meson production. In this paper we consider how the most characteristic features of hyperons and first of all Λ polarization can be accounted for in such an approach.

II. STRUCTURE OF CONSTITUENT QUARKS

We consider a nonperturbative hadron as consisting of constituent quarks located at the central part of the hadron which are embedded into a quark condensate. Experimental and theoretical arguments in favor of such a picture were given, e.g., in [16,17]. We refer to effective QCD and use the Nambu–Jona-Lasinio (NJL) model [18] as a basis. The Lagrangian in addition to the four-fermion interaction of the original NJL model includes the six-fermion $U(1)_A$-breaking term.

The transition to the partonic picture in this model is described by the introduction of a momentum cutoff $\Lambda=\Lambda_\chi\simeq 1$ GeV, which corresponds to the scale of chiral symmetry spontaneous breaking. We adopt the point that the need for such a cutoff is an effective implementation of the short distance behavior in QCD [19].

The constituent quark masses can be expressed in terms of quark condensates [19]. In this approach massive quarks appear as a quasiparticle, i.e., as the current valence quark and a surrounding cloud of quark-antiquark pairs which consists of a mixture of quarks of different flavors. It is worth stressing that in addition to u and d quarks the constituent quark (U, for example) contains pairs of strange quarks. The quantum numbers of the constituent quark are the same as the quantum numbers of the current valence quark due to the conservation of the corresponding currents in QCD. The only exception is the flavor-singlet, axial-vector current; it has a Q^2 dependence due to an axial anomaly.

The constituent quark radius is determined by the radius of the clouds and we assume that the strong interaction radius of quark Q is determined by its Compton wavelength: $r_Q=\xi/m_Q$, where the constant ξ is universal for different flavors. The quark form factor $F_Q(q)$ is taken in dipole form, viz.,

$$F_Q(q)\simeq(1+\xi^2\vec{q}\,^2/m_Q^2)^{-2}, \tag{1}$$

and the corresponding quark matter distribution $d_Q(b)$ is of the form [17]

$$d_Q(b)\propto\exp(-m_Q b/\xi). \tag{2}$$

The spin of the constituent quark J_U in this approach is given by the sum

$$J_U=1/2=J_{u_v}+J_{\{\overline{q}q\}}+\langle L_{\{\overline{q}q\}}\rangle=1/2+J_{\{\overline{q}q\}}+\langle L_{\{\overline{q}q\}}\rangle. \tag{3}$$

The value of the orbital momentum contribution to the spin of constituent quark can be estimated from the experimental results on deep-inelastic scattering [14]. Using the value for the quark contribution to the proton spin,

$$(\Delta\Sigma)_p\simeq 0.2, \tag{4}$$

and taking into account the relation between contributions of current quarks to proton spin and to spin of constituent quarks [13],

$$(\Delta\Sigma)_p=(\Delta U+\Delta D)(\Delta\Sigma)_U, \tag{5}$$

we can calculate the orbital angular momentum of $\overline{q}q$ pairs. Indeed, if we adopt[1] that $\Delta U+\Delta D=1$, then we should conclude that $J_{u_v}+J_{\{\overline{q}q\}}=1/2(\Delta\Sigma)_U\simeq 0.1$ and from Eq. (3) $\langle L_{\{\overline{q}q\}}\rangle\simeq 0.4$; i.e., about 80% of the U- or D-quark spin is due to the orbital angular momenta of u, d, and s quarks inside the constituent quark while the spin of the current valence quark is screened by the spins of the of the quark-antiquark pairs. It is also important to note the exact compensation between the spins of the quark-antiquark pairs and their angular orbital momenta:

$$\langle L_{\{\overline{q}q\}}\rangle=-J_{\{\overline{q}q\}}. \tag{6}$$

Since we consider the effective Lagrangian approach where gluon degrees of freedom are overintegrated, we do not discuss problems of the principal separation and mixing of the quark orbital angular momentum and gluon effects in QCD (cf. [21]). In the NJL model [19] the six-quark fermion operator simulates the effect of the gluon operator $(\alpha_s/2\pi)G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a$, where $G_{\mu\nu}$ is the gluon field tensor in QCD. The only effective degrees of freedom here are quasiparticles; mesons and baryons are the bound states arising due to the residual interactions between the quasiparticles.

An inclusion of the axial anomaly in the framework of chiral quark models results in compensation of the valence quark helicity by helicities of quarks from the cloud in the structure of the constituent quark [23]. The apparent physical mechanism of such compensation has been discussed recently in [8].

On these grounds we can conclude that significant parts of the spin of the constituent quark should be associated with the orbital angular momentum of quarks inside this constituent quark; i.e., the cloud quarks should rotate coherently inside the constituent quark [22].

The important point is what the origin of this orbital angular momentum is. It was proposed [15] to use an analogy with an anisotropic extension of the theory of superconductivity which seems to match well with the above picture for a constituent quark. Studies [23] of that theory show that the presence of anisotropy leads to axial symmetry of pairing correlations around the anisotropy direction $\hat{\vec{l}}$ and to the particle currents induced by the pairing correlations. In other words, it means that a particle of the condensed fluid is surrounded by a cloud of correlated particles (''hump'') which rotate around it with the axis of rotation $\hat{\vec{l}}$ [cf. Eq. (3)]. Calculation of the orbital momentum shows that it is proportional to the density of the correlated particles. Thus, it is clear that there is a direct analogy between this picture and that describing the constituent quark. An axis of anisotropy $\hat{\vec{l}}$ can be associated with the polarization vector of the valence quark located at the origin of the constituent quark. The orbital angular momentum $\vec{L}$ lies along $\hat{\vec{l}}$ [cf. Eq. (3)].

We argued that the existence of this orbital angular momentum, i.e., orbital motion of quark matter inside the constituent quark, is the origin of the observed asymmetries in inclusive production at moderate and high transverse momenta. Indeed, since the constituent quark has a small size,

$$r_Q=\xi/m_Q,\quad \xi\simeq 1/3,\quad m_Q\propto-\langle 0|\overline{q}q|0\rangle/\Lambda_\chi^2, \tag{7}$$

the asymmetry associated with the internal structure of this quark will be significant at $p_\perp>\Lambda_\chi\simeq 1$ GeV/c where interactions at short distances give a noticeable contribution.

The behavior of asymmetries in inclusive meson production was predicted [15] to have a corresponding $p_\perp$ dependence, in particular, vanishing asymmetry at $p_\perp<\Lambda_\chi$, its increase in the region of $p_\perp\simeq\Lambda_\chi$, and $p_\perp$-independent asymmetry at $p_\perp>\Lambda_\chi$. The parameter $\Lambda_\chi\simeq 1$ GeV/c is determined by the scale of chiral symmetry spontaneous breaking. Such a behavior of the asymmetry follows from the fact that the 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 the constituent quark and ''feel'' the presence of internal orbital momenta inside this constituent quark.

It should be noted that at high $p_\perp$ we will see the constituent quark being a cluster of partons which, however, should preserve their orbital momenta; i.e., the orbital angular momentum will be retained and the partons in the cluster are to be correlated. It should be stressed again that a nonzero internal orbital momentum of partons in the constituent quark means that there are significant multiparton correlations. The presence of such parton correlations is in agreement with a high locality of the strange sea in the nucleon. The concept of locality was proposed in [24] on the basis of an analysis of recent CCFR data [25] for neutrino deep-inelastic scattering. The locality serves as a measure of the local proximity of the strange quark and antiquark in momentum and coordinate spaces. It was shown [24] that the CCFR data indicate that the strange quark and antiquark have very similar distributions in momentum and coordinate spaces.

[1]We will use this simplest assumption, which is enough for our estimates. However, an inclusion of orbital and gluonic effects at the level of constituent quarks reduces $\Delta U+\Delta D$ by 25% [20,21].

III. MODEL FOR Λ-HYPERON POLARIZATION

We consider the hadron process of the type

$$h_1+h_2\to h_3^{\uparrow}+X, \tag{8}$$

with unpolarized beam and target. Usually we consider h_1 and h_2 being protons and h_3 the Λ hyperon. Its polarization is being measured through the angular distribution of products in parity-nonconserving Λ decay.

The picture of hadrons consisting of constituent quarks embedded in a quark condensate implies that overlapping and interaction of peripheral clouds occur at the first stage of hadron interactions. Under this, the condensate is being excited and as a result the quasiparticles; i.e., massive quarks appear in the overlapping region. It should be noted that the condensate excitations are massive quarks, since the vacuum is a nonperturbative one and there is no overlap between the physical (nonperturbative) and bare (perturbative) vacuum [16,18]. The part of the hadron energy carried by the outer clouds of condensates being released in the overlapping region goes to the generation of massive quarks. The number of such quarks fluctuates. The average number of these quarks in the framework of the geometrical picture can be estimated as

$$N(s,b)\propto N(s)\cdot D_c^{h_1}\otimes D_c^{h_2}, \tag{9}$$

where ⊗ denotes the convolution integral,

$$\int D_c^{h_1}(\vec{b'})D_c^{h_2}(\vec{b}-\vec{b'})d^2\vec{b'}. \tag{10}$$

The function $D_c^{h_i}$ describes condensate distribution inside hadron h_i and b is the impact parameter of colliding hadrons h_1 and h_2. To estimate the function $N(s)$ we can use the maximal possible value $N(s)\propto\sqrt{s}$ [17]. Thus, as a result massive virtual quarks appear in the overlapping region and some mean field is generated.

Constituent quarks located in the central part of the hadron are supposed to scatter in a quasi-independent way by this mean field.

We propose the following mechanism for the polarization of Λ hyperons based on the above picture for hadron structure. Inclusive production of the hyperon h_3 results from two mechanisms: recombination of the constituent quarks with virtual massive strange quarks (low $p_\perp$'s, soft interactions) into h_3 hyperons or from the scattering of a constituent quark in the mean field, excitation of this constituent quark, the appearance of a strange quark as a result of the decay of the constituent quark, and subsequent fragmentation of strange quarks in the hyperon h_3. The second mechanism is determined by the interactions at distances smaller than the constituent quark radius and is associated therefore with hard interactions (high $p_\perp$'s). This second mechanism could result from single scattering in the mean field, excitation and decay of the constituent quark, or from multiple scattering in this field with subsequent corresponding excitation and decay of the constituent quark. It is due to the multiple scattering by the mean field that the parent constituent quark becomes polarized since it has a nonzero mass [6] and this polarization results in a polarization of produced strange quarks and the appearance of the corresponding angular orbital momentum. The other mentioned mechanisms lead to the production of unpolarized Λ hyperons. Thus, we adopt a two-component picture of hadron production which incorporates interactions at long and short distances and it is the short distance dynamics which determines the production of polarized Λ hyperons.

It is necessary to note here that after decay of the parent constituent quark, current quarks appear in the nonperturbative vacuum and become quasiparticles due to the nonperturbative dressing with a cloud of $\overline{q}q$ pairs. The mechanism of this process could be associated with the strong coupling existing in the pseudoscalar channel [8,19].

Now we write down the explicit formulas for the corresponding inclusive cross sections and polarization of the hyperon h_3. The following expressions were obtained in [26] which take into account unitarity in the direct channel of reaction. They have the form

$$\frac{d\sigma^{\uparrow,\downarrow}}{d\xi}=8\pi\int_0^\infty bdb\frac{I^{\uparrow,\downarrow}(s,b,\xi)}{|1-iU(s,b)|^2}, \tag{11}$$

where b is the impact parameter of colliding hadrons. Here the function $U(s,b)$ is the generalized reaction matrix (helicity nonflip one) which is determined by the dynamics of the elastic reaction

$$h_1+h_2\to h_1+h_2. \tag{12}$$

Arrows here denote the corresponding transverse polarization of the hyperon h_3.

The functions $I^{\uparrow,\downarrow}(s,b,\xi)$ are related to the functions $U_n(s,b,\xi,\{\xi_{n-1}\})$ which are the multiparticle analogues of the $U(s,b)$ and are determined by dynamics of the exclusive processes

$$h_1+h_2\to h_3^{\uparrow,\downarrow}+X_{n-1}. \tag{13}$$

The kinematical variables ξ (x and $p_\perp$, for example) describe the kinematical variables of the produced hyperon h_3 and the set of variables $\{\xi_{n-1}\}$ describe the system X_{n-1} of $n-1$ particles. It is useful to introduce the two functions I_+ and I_-:

$$I_\pm(s,b,\xi)=I^{\uparrow}(s,b,\xi)\pm I^{\downarrow}(s,b,\xi), \tag{14}$$

where $I_+(s,b,\xi)$ corresponds to the unpolarized case. The following sum rule takes place for the function $I_+(s,b,\xi)$:

$$\int I_+(s,b,\xi)d\xi=\overline{n(s},b)\mathrm{Im}U(s,b), \tag{15}$$

where $\overline{n(s},b)$ is the mean multiplicity of secondary particles in the impact parameter representation.

The polarization P, defined as the ratio

$$P(s,\xi)=\left\{\frac{d\sigma^{\uparrow}}{d\xi}-\frac{d\sigma^{\downarrow}}{d\xi}\right\}\Bigg/\left\{\frac{d\sigma^{\uparrow}}{d\xi}+\frac{d\sigma^{\downarrow}}{d\xi}\right\}, \tag{16}$$

can be expressed in terms of the functions $I_\pm$ and U:

$$P(s,\xi)=\int_0^\infty bdbI_-(s,b,\xi)/|1-iU(s,b)|^2 \Big/ \int_0^\infty bdbI_+(s,b,\xi)/|1-iU(s,b)|^2. \quad (17)$$

Using the relations between transversely polarized states $|\uparrow,\downarrow\rangle$ and helicity states $|\pm\rangle$, one can write down expressions for I_+ and I_- through the helicity functions $U_{\{\lambda_i\}}$:

$$I_+(s,b,\xi)=\sum_{n,\lambda_1,\lambda_2,\lambda_3,\lambda_{X_{n-1}}} n\int d\Gamma_{n-1}|U_{n,\lambda_1,\lambda_2,\lambda_3,\lambda_{X_{n-1}}}(s,b,\xi,\{\xi_{n-1}\})|^2, \quad (18)$$

$$I_-(s,b,\xi)=\sum_{n,\lambda_1,\lambda_2,\lambda_{X_{n-1}}} 2n\int d\Gamma_{n-1}\mathrm{Im}[U_{n,\lambda_1,\lambda_2,+,\lambda_{X_{n-1}}}(s,b,\xi,\{\xi_{n-1}\})U^*_{n,\lambda_1,\lambda_2,-,\lambda_{X_{n-1}}}(s,b,\xi,\{\xi_{n-1}\})]. \quad (19)$$

Here the $\lambda_{X_{n-1}}$ denotes the set of helicities of particles from the X_{n-1} system; note that in general this system as a whole has no definite spin or helicity.

Since in the model constituent quarks are quasi-independent ones and the production of the hyperon h_3 is the result of the interaction of one of them with the mean field, we can write the helicity functions $U_{\{\lambda_i\}}$ as a sum $U_{\{\lambda_i\}}=\Sigma_j U^{Q_j}_{\{\lambda_i\}}$ or simply as $U_{\{\lambda_i\}}=NU^{Q}_{\{\lambda_i\}}$ taking into account that there are no constituent strange quarks among the N initial quarks in the colliding hadrons h_1 and h_2 (we do not consider here the processes with initial hadrons containing strange quarks and therefore all constituent quarks are considered to be equivalent with respect to the production of the hyperon h_3). The superscript Q denotes that the helicity function $U^Q_{\{\lambda_i\}}$ describes the production of the hyperon h_3 as a result of interaction a quark Q with the mean field.

In the model the spin-independent part $I^Q_+(s,b,\xi)$ [note that $I_\pm(s,b,\xi)=N^2 I^Q_\pm(s,b,\xi)$] gets a contribution from the processes at small (hard) processes as well as at large (soft) processes distances, i.e.,

$$I^Q_+(s,b,\xi)=I^{hQ}_+(s,b,\xi)+I^{sQ}_+(s,b,\xi), \quad (20)$$

while the spin-dependent part $I^Q_-(s,b,\xi)$ gets a contribution from the interactions at short distances only:

$$I^Q_-(s,b,\xi)=I^{hQ}_-(s,b,\xi). \quad (21)$$

The presence of internal orbital momenta in the structure of the constituent quark means that current quarks have intrinsic transverse momenta the magnitude of which can be estimated from the relation

$$\langle L_{\{\bar{q}q\}}\rangle=r_Q\langle k_\perp\rangle. \quad (22)$$

It leads to a shift in the transverse momentum of the final hyperon, i.e., $p_\perp\to p_\perp+k_\perp$. We suppose on the basis of Eq. (6) that there is a compensation between spin and orbital momentum of strange quarks inside a constituent quark: i.e.,

$$L_{s/Q}=-J_{s/Q}. \quad (23)$$

It seems to be a natural assumption and due to this the effects of the shift of the transverse momenta and polarization of the Λ hyperon are directly connected since the spin and polarization of the Λ hyperon are completely determined by those of the strange quark in the simple SU(6) scheme. Equation (23) is quite similar to the conclusion made in the framework of the Lund model [4], but has a different dynamical origin rooted in the mechanism of the spontaneous breaking of chiral symmetry.

Taking into account the quasi-independence of the constituent quark scattering in the mean field together with the assumption on hyperon production as a result of the multiple scattering of the constituent quark in the mean field, we use the following expressions for the functions $I^{hQ}_\pm(s,b,\xi)$:

$$I^{hQ}_\pm(s,b,\xi)=\overline{n(s,b)}\,\mathrm{Im}\left(\prod_{i=1}^{N-1}\langle f_{Q_i}(s,b)\rangle\langle\varphi^\pm_{h_3/Q}(s,b,\xi)\rangle\right). \quad (24)$$

The factors $\langle f_{Q_i}(s,b)\rangle$ correspond to the individual constituent quark scattering amplitude smeared over the transverse position of the quark Q_i and over the fraction of the longitudinal momentum carried by the quark Q_i. The functions $\langle\varphi^\pm_{h_3/Q}(s,b,\xi)\rangle$ describe the production of the hyperon h_3 as a result of the interaction of the constituent quark Q with the mean field and can be represented as a sum and difference of the two functions $\langle\varphi^\uparrow_{h_3/Q}(s,b,\xi)\rangle$ and $\langle\varphi^\downarrow_{h_3/Q}(s,b,\xi)\rangle$: i.e.,

$$\langle\varphi^\pm_{h_3/Q}(s,b,\xi)\rangle=\langle\varphi^\uparrow_{h_3/Q}(s,b,\xi)\rangle\pm\langle\varphi^\downarrow_{h_3/Q}(s,b,\xi)\rangle. \quad (25)$$

The essential point here is the connection of the hyperon polarization with the orbital angular momentum of strange quarks located inside the constituent quark.

The functions $\langle\varphi^\pm_{h_3/Q}\rangle$ can be written in the form of the convolution integrals:

$$\langle\varphi^\pm_{h_3/Q}\rangle=\langle\varphi^\pm_{s/Q}\rangle\otimes D_{h_3/s}, \quad (26)$$

where $D_{h_3/s}$ is a fragmentation function. It is supposed to be a spin-independent one. The functions $\langle\varphi^\pm_{s/Q}\rangle$ describe the internal structure of the constituent quark. The spin-dependent one $\langle\varphi^-_{s/Q}\rangle$ accounts also for the effect of the nonzero orbital angular momentum of the strange quark inside the constituent quark. As has been noted, this internal orbital momentum leads to a shift in the transverse momentum of the produced hyperon. Thus, we assume that the spin-dependent function $\langle \varphi^{-}_{h_3/Q}\rangle$ can be obtained by shifting the transverse momentum in the argument of the spin-independent one, i.e., $\langle \varphi^{+}_{h_3/Q}\rangle$. Indeed, at high transverse momenta this shift can be reduced to a phase factor in the impact parameter representation; i.e., we will have the relations

$$\langle \varphi^{-}_{h_3/Q}(s,b,x,b')\rangle \simeq \exp[ik_{\perp s/Q}b']\langle \varphi^{+}_{h_3/Q}(s,b,x,b')\rangle, \tag{27}$$

where

$$\langle \varphi^{+}_{h_3/Q}(s,b,x,b')\rangle = \int d^2p_\perp \exp(i\vec{b'}\vec{p_\perp}) \times \langle \varphi^{+}_{h_3/Q}(s,b,x,p_\perp)\rangle. \tag{28}$$

Then taking into account that the quark matter distribution inside the constituent quark has the radius r_Q, we can write the approximate relation

$$k_{\perp s/Q} r_Q \simeq L_{s/Q}. \tag{29}$$

On the basis of the above discussion, we assume the following relation between the functions $I_{-}^{hQ}(s,b,\xi)$ and $I_{+}^{hQ}(s,b,\xi)$:

$$I_{-}^{hQ}(s,b,\xi) = \sin[L_{s/Q}] I_{+}^{hQ}(s,b,\xi). \tag{30}$$

The sign of $L_{s/Q}$ is determined by the direction of rotation of $q\bar{q}$ pairs inside the constituent quark and is correlated with the sign of the constituent quark polarization.

The total orbital angular momentum of quark-antiquark pairs in the constituent quark Q which has polarization $\mathcal{P}_Q(x)$ is

$$\langle L_{\{\bar{q}q\}}\rangle^{\mathcal{P}_Q(x)} = \mathcal{P}_Q(x)\langle L_{\{\bar{q}q\}}\rangle, \tag{31}$$

where the value of $\langle L_{\{\bar{q}q\}}\rangle$ enters the spin balance, Eq. (3), written for the constituent quark with polarization $+1$. Since the value of the orbital angular momentum of $s\bar{s}$ quarks in the constituent quark Q is proportional to the orbital momentum in the constituent quark $\langle L_{\{\bar{q}q\}}\rangle^{\mathcal{P}_Q(x)}$, we can write for $L_{s/Q}$ the relation

$$L_{s/Q} = \mathcal{P}_Q(x)\alpha\langle L_{\{\bar{q}q\}}\rangle, \tag{32}$$

where the parameter α determines the fraction of orbital angular momentum due to the strange quarks. Thus we can rewrite the relation between $I_{-}^{hQ}(s,b,\xi)$ and $I_{+}^{hQ}(s,b,\xi)$ in the form

$$I_{-}^{hQ}(s,b,\xi) = \sin[\mathcal{P}_Q(x)\alpha\langle L_{\{\bar{q}q\}}\rangle] I_{+}^{hQ}(s,b,\xi). \tag{33}$$

The polarization of the constituent quark $\mathcal{P}_Q(x)$ arises due to multiple scattering in the mean field. Note that we consider the behavior of polarization in the fragmentation region (where $x_F \simeq x$).

Thus, in this model polarization of the strange quark is a result of the multiple scattering of the parent constituent quark, the correlation between the polarization of the strange quark and polarization of the constituent quark-and-local compensation of spin and orbital angular momentum of the strange quark [cf. Eq. (23)]. The nonzero orbital angular momentum leads to the shift in the transverse momentum of the s quark and produced Λ hyperon. This is the reason for the appearance of the factor $\sin[L_{s/Q}]$ in Eq. (30).

The x dependences of the functions $I_{+}^{sQ}(s,b,\xi)$ and $I_{+}^{hQ}(s,b,\xi)$ are determined by the distribution of constituent quarks in hadrons and by the structure function of the constituent quark, respectively [15]:

$$I_{+}^{sQ}(s,b,\xi) \propto \tfrac{1}{2}[\omega_{Q/h_1}(x) + \omega_{Q/h_2}(x)]\Phi^{sQ}(s,b,p_\perp) \tag{34}$$

and

$$I_{+}^{hQ}(s,b,\xi) \propto \omega_{s/Q}(x)\Phi^{hQ}(s,b,p_\perp). \tag{35}$$

Taking into account the above relations, we can represent the polarization P in the form

$$P(s,x,p_\perp) = \sin[\mathcal{P}_Q(x)\alpha\langle L_{\{\bar{q}q\}}\rangle] W_{+}^{hQ}(s,\xi)/[W_{+}^{sQ}(s,\xi) + W_{+}^{hQ}(s,\xi)], \tag{36}$$

where the functions $W_{+}^{s,hQ}$ are determined by the interactions at long (s) and short (h) distances:

$$W_{+}^{s,hQ}(s,\xi) = \int_0^\infty bdb I_{+}^{s,hQ}(s,b,\xi)/|1 - iU(s,b)|^2. \tag{37}$$

IV. BEHAVIOR OF Λ POLARIZATION

As has been already noted, we consider the most simple case of Λ-hyperon production. In this case spin and polarization of the hyperon h_3 is completely determined by the spin and polarization of the s quark from the internal structure of the parent constituent quark. The latter acquires its polarization due to multiple scattering in the mean field. This polarization is negative; e.g., in gluon external field it is [6]

$$\mathcal{P}_Q \propto -I\frac{m_Q g^2}{\sqrt{s}}. \tag{38}$$

It could have a significant value since the constituent quark in our case has a nonzero mass $m_Q \sim m_h/3$ and the intensity of the mean field in the model should be taken as

$$I \propto \sqrt{s}, \tag{39}$$

since it is generated by the quasiparticles whose average number is rising with energy like $\sqrt{s}$ [17]. Note that g in Eq. (38) is the coupling constant of the quark interaction with an external field. Thus, the constituent quark polarization [cf. Eq. (38)] is roughly constant with energy.

On the basis of the above considerations, we take an assumption that the polarization of the constituent quark is energy independent and it is approaching the maximal value -1 at $x=1$. The assumption about the maximality of the polarization at the constituent level has been made on the basis of recent data of the ALEPH Collaboration [27] which made such an indication in the analysis of Λ_b polarization in the e^+e^- interaction.

We take also the simplest possible x dependence of $\mathcal{P}_Q(x)$, i.e., the linear one:

$$\mathcal{P}_Q(x)=\mathcal{P}_Q^{\max}x, \tag{40}$$

where $\mathcal{P}_Q^{\max}=-1$.

The behavior of Λ polarization in the model has a significantly different x and $p_\perp$ dependences in the regions of small and large transverse momenta $p_\perp \leqslant \Lambda_\chi$ and $p_\perp \geqslant \Lambda_\chi$. It is convenient to introduce the ratio

$$R(s,\xi)=\frac{W_+^h(s,\xi)}{W_+^s(s,\xi)}=\frac{2\omega_{s/Q}(x)}{\omega_{Q/h_1}(x)+\omega_{Q/h_2}(x)}r(s,p_\perp), \tag{41}$$

where the function $r(s,p_\perp)$ in its turn is the x-independent ratio

$$r(s,p_\perp)=\frac{\int_0^\infty bdb\Phi^h(s,b,p_\perp)/|1-iU(s,b)|^2}{\int_0^\infty bdb\Phi^s(s,b,p_\perp)/|1-iU(s,b)|^2}. \tag{42}$$

The expression for the polarization can be rewritten in the form

$$P(s,x,p_\perp) =\sin[\mathcal{P}_Q(x)\alpha\langle L_{\{\overline{qq}\}}\rangle]R(s,x,p_\perp)/[1+R(s,x,p_\perp)]. \tag{43}$$

The function $R(s,x,p_\perp)\gg 1$ at $p_\perp > \Lambda_\chi$ since in this region short distance processes dominate and, due to a similar reason, $R(s,x,p_\perp)\ll 1$ at $p_\perp \leqslant \Lambda_\chi$. Thus we have a simple $p_\perp$-independent expression for the polarization at $p_\perp > \Lambda_\chi$,

$$P(s,x,p_\perp)\simeq\sin[\mathcal{P}_Q(x)\alpha\langle L_{\{\overline{qq}\}}\rangle], \tag{44}$$

and a more complicated one for the region $p_\perp \leqslant \Lambda_\chi$:

$$P(s,x,p_\perp)\simeq\sin[\mathcal{P}_Q(x)\alpha\langle L_{\{\overline{qq}\}}\rangle] \times\frac{2\omega_{s/Q}(x)}{\omega_{Q/h_1}(x)+\omega_{Q/h_2}(x)}r(s,p_\perp). \tag{45}$$

As is clearly seen from Eq. (45), the polarization at $p_\perp \leqslant \Lambda_\chi$ has a nontrivial $p_\perp$ dependence. In this region the polarization vanishes at small $p_\perp$ and is also suppressed by the factor $2\omega_{s/Q}(x)/[\omega_{Q/h_1}(x)+\omega_{Q/h_2}(x)]$, which can be considered as the ratio of sea and valence quark distributions in hadrons. The x dependence of the polarization in this kinematical region strongly depends on the particular parametrization of these distributions. However, this dependence in the region of transverse momenta $p_\perp > \Lambda_\chi$ has a simple form, reflecting the corresponding dependence constituent quark polarization. The curve for the polarization at $p_\perp > \Lambda_\chi$ corresponding to the linear dependence of $\mathcal{P}_Q(x)$ is presented in Fig. 1. The value of $\langle L_{\{\overline{qq}\}}\rangle \simeq 0.4$ has been taken [15] on the basis of the analysis [14] of the deep inelastic scattering (DIS) experimental data. To get agreement with experimental data we take the value of the parameter $\alpha=0.8$. Using the above value of the quark angular orbital momentum we obtain good agreement with the data in the case of the linear dependence of the constituent quark polarization. Note that

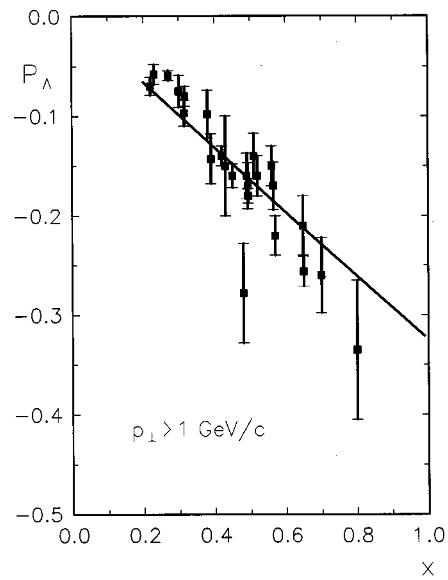

FIG. 1. The x dependence of Λ-hyperon polarization in the process $pp\to\Lambda X$ at $p_L=400$ GeV/c.

here we have assumed that the spin structure of the transversely polarized constituent quark is the same as the spin structure of the longitudinally polarized constituent quark.

The qualitative $p_\perp$ dependence of the polarization described above also is in good agreement with corresponding experimental data. To describe quantitatively the $p_\perp$ dependence of Λ polarization, in particular, in the region $p_\perp \leqslant \Lambda_\chi$, we should chose an explicit parametrization of the cross-section ratio $R(s,x,p_\perp)$ for the hard and soft processes. For that purpose we can consider the simplest parametrization of the function $R(s,x,p_\perp)$:

$$R(s,x,p_\perp)=C(x)\exp(p_\perp/m)/(p_\perp^2+\Lambda_\chi^2)^2. \tag{46}$$

Such a parametrization implies the typical behavior of the cross sections of soft [exponential, $\exp(-p_\perp/m)$] and hard (powerlike) processes. We take $m=0.2$ GeV which sets the scale of soft interactions at 1 fm and $\Lambda_\chi=1$ GeV/c in quantitative agreement with the experimental trends.

As an example we consider data at $x=0.44$ which cover a wide range of $p_\perp$'s. The magnitude of $C(x)$ at the above value of x is chosen to be 0.2 to get agreement with the experimental data. The corresponding curve and experimental data are given in Fig. 2 and as can be easily seen agreement with experiment is good.

It should be noted that the qualitative arguments discussed at the beginning of this section indicate no energy dependence for Λ polarization.

V. CONCLUSION AND DISCUSSION

Now we summarize the main results of the considered model.

Polarization of Λ hyperons arises as a result of the internal structure of the constituent quark and its multiple scattering in the mean field. It is proportional to the orbital angular momentum of strange quarks initially confined in the constituent quark.

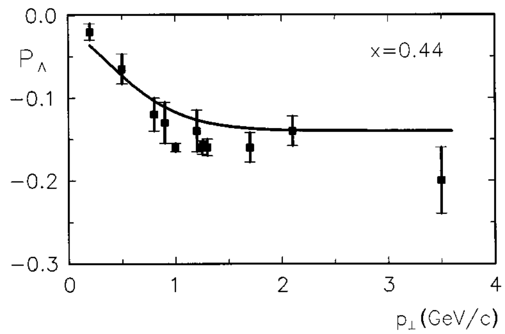

FIG. 2. The $p_\perp$ dependence of Λ-hyperon polarization in the process $pp \to \Lambda X$ at $p_L = 400$ GeV/c.

The sign of polarization and its value are proportional to the polarization of the constituent quark gained due to the multiple scattering in the mean field.

The main role in the model belongs to the orbital angular momentum of $\bar{q}q$ pairs inside the constituent quark while constituent quarks themselves have very slow (if at all) orbital motion and may be described approximately by an S state of the hadron wave function. The observed $p_\perp$ dependence of Λ-hyperon polarization in inclusive processes seems to confirm such conclusions, since it appears to show up beyond $p_\perp > 1$ GeV/c, i.e., the scale where the internal structure of the constituent quark can be probed. Note that a short-distance interaction in this approach observes coherent rotation of correlated $\bar{q}q$ pairs inside the constituent quark and not a gas of free partons.

We have considered the most simple case of Λ-hyperon polarization. As a whole problem, the case of hyperon polarization is extremely complicated and many reactions we did not attempt to account for and many questions are left unanswered. However, a few comments on the other reactions and the underlying mechanism we could make. First, we would like to note that experimental data show that proton polarization in the inclusive process $pp \to pX$ is zero. This fact can easily be understood in the model. Indeed, multiple scattering of constituent quarks in the mean field has a lower probability compared to single scattering. Single scattering does not polarize quarks and protons appear unpolarized in the final state since single scattering is dominant in this process. On the other hand, multiple scattering, excitation, and decay of constituent quarks are correlated mechanisms, which is the reason for the Λ-hyperon polarization in the model. Of course, $\bar{s}$ quarks also will be produced polarized, but contrary to s quarks, which can easily recombine with constituent quarks of parent protons to produce Λ, the $\bar{s}$ quark has no such possibility and should pick up virtual massive quarks generated at the condensate interaction. Since polarization of produced $\bar{\Lambda}$ hyperons in the process $pp \to \bar{\Lambda} X$ is almost zero, we should conclude that the latter mechanism implies strong depolarization dynamics. Thus we have to suppose different mechanisms of Λ and $\bar{\Lambda}$ formation at the final state. Those mechanisms have comparable strength at $x=0$, but $\bar{\Lambda}$ production has to be suppressed at large x in agreement with the experimental data [1]. To describe the very different behavior of polarization in other hyperon production and the possible energy dependence observed in some reactions it seems that we need very detailed knowledge of fragmentation dynamics [27,28] which is unattainable at the moment.

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