Challenge of Hyperon Polarization

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It was discovered in 1976 that in collision of unpolarized protons

$$p + p \to \Lambda + X$$

Λ–hyperons are produced strongly polarized.

$$P_\Lambda = \frac{d\sigma^{pp\to\Lambda_\uparrow X} - d\sigma^{pp\to\Lambda_\downarrow X}}{d\sigma^{pp\to\Lambda_\uparrow X} + d\sigma^{pp\to\Lambda_\downarrow X}}.$$

Wealth of experimental data on hyperon polarization in inclusive reactions.

Polarization of Λ enters proton angular distribution in parity non-conserving decay

$$\Lambda \to p + \pi^-$$

$$\frac{dN}{d\cos\theta^*} = N_0(1 + \alpha P_\Lambda \cos\theta^*),$$

$\alpha = 0.64$, θ^* – angle between the momentum of a proton produced in the decay of Λ and the polarization vector of Λ–particle in its rest frame.

Polarization of Λ is obtained from $\cos\theta^*$–distribution analysis.

Experimental regularities:

- Polarization of inclusively produced Λ is negative, i.e. its direction is opposite to the vector $\vec{p} \times \vec{p}_\Lambda$, ($\vec{p}$ is incident particle momentum).
  Polarization increases with transverse momentum of Λ–particle
  and at $p_\perp > 0.8 - 1.0$ GeV/c dependence of P_Λ on transverse momentum is weak. In this region of $p_\perp$, the polarization of Λ grows linearly with x_F.
  At the maximal $p_\perp \simeq 3.5$ GeV/c no tendency to decrease for polarization was observed.

- Λ–hyperon polarization is energy independent in a wide range of laboratory energies $p_{Lab} = 12 - 2000$ GeV/c.

- In proton–proton interactions:

$$P_{\Sigma^0} \simeq P_{\Sigma^-} \simeq P_{\Sigma^+} \simeq -P_{\Lambda} \simeq -P_{\Xi^0} \simeq -P_{\Xi^-},$$

$$P_{\bar{\Lambda}} \simeq P_p \simeq P_{\Omega^-} \simeq 0,$$

$$P_{\Lambda}(p \to \Lambda) \simeq P_{\bar{\Lambda}}(\bar{p} \to \bar{\Lambda}).$$

In meson reactions

$$P_{\Lambda}(K^- \to \Lambda) > 0,$$

$$|P_{\Lambda}(K^- \to \Lambda)| \gg |P_{\Lambda}(p \to \Lambda)|.$$

and

$$|P_{\bar{\Lambda}}(K^+ \to \bar{\Lambda})| \gg |P_{\bar{\Lambda}}(\bar{p} \to \bar{\Lambda})|.$$

- In exclusive diffractive process

$$p + p \to p + [\Lambda^0 K^+]$$

polarization increases linearly with $p_\perp$ at $\sqrt{s} \simeq 30$ GeV and gets very large value, $P_{\Lambda} \simeq 80\%$ at $p_\perp \simeq 1$ GeV/c.

Severe problems for theory: PQCD, NPQCD, Models.

Even Λ -polarization has no satisfactory explanation.

Perturbative QCD

Chiral invariance and vector nature of QCD-interaction provide important consequences for spin observables.

QCD Lagrangian – invariant under $SU(3)_L \times SU(3)_R$ group ($N_f = 3$).

QCD interactions are the same for left and right quarks:

$$\bar{\psi}\gamma_\mu\psi A^\mu = \bar{\psi}_L\gamma_\mu\psi_L A^\mu + \bar{\psi}_R\gamma_\mu\psi_R A^\mu\,.$$

Left–handed (right–handed) massless particles will always stay left handed (right–handed).

For massless quarks chirality and helicity coincide.

If the quarks have a non–zero mass chirality and helicity are equal approximately at high energies, namely:

$$\psi_{1/2} = \psi_R + O\left(\frac{m}{\sqrt{\hat{s}}}\right)\psi_L,$$

$$\psi_{-1/2} = \psi_L + O\left(\frac{m}{\sqrt{\hat{s}}}\right)\psi_R$$

$\pm 1/2$ are the quark helicities.

Any quark line entering Feynman diagram corresponding to QCD Lagrangian emerges from it with unaltered helicity. Quark helicity conservation is the most characteristic feature of this theory.

To get $P_q \neq 0$ we need helicity flip amplitude being a non–zero one and the phases of helicity flip F_f and non–flip F_{nf} amplitudes should be different, since

$$P \propto \mathrm{Im}(F_{nf}F_f^*).$$

In QCD the quark helicity flip amplitude is of order of $m/\sqrt{\hat{s}}$ and in Born approximation amplitudes are real and it is necessary to consider the diagrams of higher orders, i.e. quark helicity flip amplitude is proportional

$$F_f^q \propto \frac{\alpha_s m_q}{\sqrt{\hat{s}}} F_{nf}^q$$

and quark polarization is vanishingly small in hard interactions:

$$P_q \propto \frac{\alpha_s m_q}{\sqrt{\hat{s}}}$$

due to large value of $\sqrt{\hat{s}} \sim p_\perp$ and small values of α_s and m_q, where m_q stands for mass of current quark.

Explicit calculation of s-quark polarization in gluon fusion provides $P_s \leq 4\%$.

Straightforward collinear factorization then leads to very small P_Λ.

Twist-3 contribution

$$E_a(x_1,x_2)\otimes q_b(x')\otimes \delta D_{c\to\Lambda}(z)\otimes \hat\sigma_{ab\to c}.$$

Function $E_a(x_1,x_2)$ – twist-3 unpolarized distribution. There is no any information on these functions — assumptions and models are necessary.

$$P_\Lambda \sim \frac{m_p b(x_1,x_2)}{p_\perp}$$

Decreasing dependence $P_\Lambda \sim 1/p_\perp$ does not fit data

Dynamical origin of quark polarization is obscured.

Modification of collinear factorization: role of $k_\perp$-effects.

$k_\perp$-effects in distribution functions are not possible:

problems with T–invariance.

$k_\perp$-effects in factorization functions:

$$\Delta^N D_{h_\uparrow/a}(z,\mathbf{k}_\perp) \equiv \hat{D}_{h_\uparrow/a}(z,\mathbf{k}_\perp) - \hat{D}_{h_\downarrow/a}(z,\mathbf{k}_\perp)$$

$$= \hat{D}_{h_\uparrow/a}(z,\mathbf{k}_\perp) - \hat{D}_{h_\uparrow/a}(z,-\mathbf{k}_\perp),$$

Analogy with Collins' suggestion for the fragmentation of a transversely polarized quark:

$$\hat{D}_{h^\uparrow/q}(z,\mathbf{k}_\perp) = \frac{1}{2}\,\hat{D}_{h/q}(z,k_\perp)$$

$$+\frac{1}{2}\,\Delta^N D_{h^\uparrow/q}(z,k_\perp)\,\frac{\hat{\mathbf{P}}_h\cdot(\mathbf{p_q}\times\mathbf{k}_\perp)}{|\mathbf{p_q}\times\mathbf{k}_\perp|}$$

Generalized factorization scheme – with inclusion of intrinsic transverse motion – with pQCD dynamics; new, spin and $\mathbf{k}_\perp$ dependent, polarizing fragmentation function.

Source of Λ polarization is polarizing fragmentation function $\Delta^N D_{h_\uparrow/a}(z,\mathbf{k}_\perp)$.

- $1/p_\perp$ – dependence at large $p_\perp$ ($\sim \langle k_\perp \rangle / p_\perp$).

- need a model for polarizing FF, dynamical origin is unclear

- disagreement with e^+e^- - data, no significant transverse polarization of Λ was found at LEP.

General conclusion: situation with Λ polarization within pQCD is unsatisfactory.

Non-perturbative models

These models exploit confinement and chiral symmetry breaking
Classical string (Lund) model, Thomas precession: partial agreement with experiment.

$SU(3)_L \times SU(3)_R$ group of QCD Lagrangian is not realized in hadron spectrum.

In real world the chiral $SU(3)_L \times SU(3)_R$ group is broken down to $SU(3)_V$ with appearance of Goldstone bosons.

Chirality is not symmetry of QCD, it is broken (hidden) by the vacuum state

$$\langle 0|\bar{\psi}\psi|0\rangle = \langle 0|\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L|0\rangle.$$

Scale $\Lambda_\chi \simeq 4\pi f_\pi \simeq 1$ GeV, (f_π is pion decay constant).

Chiral symmetry breaking generates quark masses:

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

Massive quarks are quasiparticles, (current quark surrounded by cloud of quark–antiquark pairs of different flavors).

Constituent quark (U, for example) contains pairs of strange quarks.

Spin of constituent quark J_U is

$$J_U = 1/2 \;=\; S_{u_v} + S_{\{\bar{q}q\}} + L_{\{\bar{q}q\}} = 1/2 + S_{\{\bar{q}q\}} + L_{\{\bar{q}q\}}$$

$$\frac{1}{2}(\Delta\Sigma)_U = 1/2 + S_{\{\bar{q}q\}},$$

$$(\Delta\Sigma)_p = (\Delta U + \Delta D)(\Delta\Sigma)_U; \;\; (\Delta\Sigma)_p \simeq 0.2,$$

$$L_{\{\bar{q}q\}} \simeq 0.4$$

Orbital angular momentum (orbital motion of quark matter inside constituent quark) is the origin of asymmetries in inclusive production with polarized target at moderate and high transverse momenta.

Polarization of Λ–hyperon is result of polarization of constituent quark due to multiple scattering in the effective field.

It implies the s-quark polarization inside the constituent quark

Geometrical size of constituent quark

$$R_Q \simeq 1/\Lambda_\chi$$

Polarization is significant when interaction resolve internal structure of constituent quark $r < R_Q$, i. e. at $p_\perp > \Lambda_\chi \simeq 1$ GeV/c.

The behavior of polarization (and asymmetries) in inclusive meson production have typical $p_\perp$–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 $p_\perp > \Lambda_\chi$.

At high $p_\perp$ we shall 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.

Nonzero internal orbital momentum of partons in the constituent quark means that there are significant multiparton correlations. High locality of strange sea in the nucleon was found experimentally (CCFR collaboration.)

Experimentally observed persistence and constancy of polarization of Λ–hyperon means that chiral symmetry is not restored and quark-gluon phase has not been reached yet.

Absence or strong diminishing of hyperon polarization can be considered as a signal of quark-gluon plasma formation.

When the density in nuclear–nuclear collisions is higher than critical, we can expect that

$$P_\Lambda(b) \to 0$$

when impact parameter $b \to 0$.
Otherwise (when there is no region where QGP have been formed) the impact parameter dependence of $P_\Lambda(b)$ would be flat.
Decreasing with b polarization of Λ could serve as an signal of the quark–gluon plasma formation
Impact parameter b is controllable by centrality

Experimental strategy:

- ♣ Measurement of P_Λ in pp–interactions: If at high $p_\perp$

$$P_\Lambda = 0$$

Perturbative QCD region has been reached, OK with perturbative estimates of QCD background and so on.

- ♣ But if at high $p_\perp$ $P_\Lambda \neq 0$ then even in the hard region there is a significant role of nonperturbative dynamics. Use polarization of Λ as a signal of QGP formation.

Are the Λ–polarization measurements experimentally feasible?
In principle –yes, due to its parity non-conserving decay.
At CMS inner tracker could be used to measure polarization of Λ at high $p_{\perp}$.
It would be interesting to measure polarization of Λ in the TOTEM kinematical region too.