WHAT CAN WE LEARN FROM POLARIZED BEAMS

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Spin physics studies provide crucial information on such fundamental issues as

- hadron wave functions and nucleon structure.
- interplay of large and short distance dynamics.
- chiral symmetry breaking and confinement.

To proceed in understanding of the field one should answer the questions:

- how the constituents' interactions depend on spin?
- what is a picture of the nucleon structure, in particular its spin structure?

Systematic studies of this subject [1,2,3] require the use of polarized beams. At present the most attractive options for advancing are as follows:

$\vec{e}\vec{p}$-collisions (HERA and SLAC),

$\vec{\mu}\vec{p}$-collisions (CERN-SMC),

$\vec{p}\vec{p}$, $p_\uparrow p_\uparrow$-collisions (RHIC).

One should note that the using beams of polarized partons (polarized proton-proton collisions) at RHIC will force us again to pay attention to further justification of perturbative QCD (step to higher energies) and to account for nonperturbative effects as well.

The spin asymmetries are those parameters which are examined experimentally. In terms of the corresponding helicity amplitudes $F(...)$ we have for one-spin asymmetries

$$A_L = \frac{d\sigma(+) - d\sigma(-)}{d\sigma(+) + d\sigma(-)} \propto (|F(+)|^2 - |F(-)|^2),$$

where $d\sigma(\pm)$ are cross-sections for the two different helicities of one of the particles in the process and

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \propto Im(F(+)F^*(-)),$$

when spin vector is in the transverse direction.

A nonzero value of A_L means appearance of parity violation effects. A nonzero A_N can appear in perturbative QCD from higher twists. Among the possible sources of $A_N \neq 0$ one should mention correlation between constituents $k_\perp$'s and their spins in the structure [4] and fragmentation functions [5], the significant role of orbital angular momentum of the constituents inside a hadron [6]. At present the data on one-spin transverse asymmetries do not consent with the perturbative QCD conclusion $A_N = 0$.

For the two-spin asymmetries in the above notations we have respectively

$$A_{LL} = \frac{d\sigma(++) - d\sigma(+-)}{d\sigma(++) + d\sigma(+-)} \propto (|F(++)|^2 - |F(+-)|^2),$$

$$A_{LL} = \frac{d\sigma(++) - d\sigma(--)}{d\sigma(++) + d\sigma(--)} \propto (|F(++)|^2 - |F(--)|^2),$$

$$A_{NN} = \frac{d\sigma(\uparrow\uparrow) - d\sigma(\uparrow\downarrow)}{d\sigma(\uparrow\uparrow) + d\sigma(\uparrow\downarrow)} \propto Re(M(++)M^*(+-)).$$

First, we note that A_{LL} and A_{NN} get nonzero values already in the leading order. So, these asymmetries could be useful for studying the parton spin densities.

Usually we use factorization as the basic tool to obtain QCD predictions for hard processes. It separates long distance bound state dynamics and short distance constituents' interactions.

In general the scheme can be easily traced from the equation:

$$\sigma_{AB} = \sum_{a,b} f_{a/A} \otimes H_{ab} \otimes f_{b/B} + O\left(\Lambda^2/Q^2\right).$$

Here $f_{a/A}(x_a, Q)$ stands for the universal distribution functions (light-cone parton densities), which are nonperturbative objects and can be extracted from D1S data. The hard part H_{ab} is the short distance cross-section for parton-parton scattering. It can be expanded in powers of the running coupling constant $\alpha_s(Q^2) \sim \ln^{-1} Q^2/\Lambda^2$.

With the use of factorization the measured asymmetries can be written for variety of processes. For instance,

a) $p_\uparrow + p \to h + X$

$$A_N \propto \sum_{ab\to cd} \int dx_a dx_b \frac{dz}{z} \Delta_N f_{a/p}(x_a) f_{b/p}(x_b) \hat{a}_N \hat{\sigma}(ab \to cd) D_{h/c}(z);$$

b) $\vec{p} + \vec{p} \to h + X$

$$A_{LL} \propto \sum \int \Delta_L f_{a/p} \Delta_L f_{b/p} \hat{a}_{LL} \hat{\sigma} D_{h/c};$$

c) $p + p \to \Lambda_\uparrow + X$

$$A_N \propto \sum \int f_{a/p} f_{b/p} \hat{a}_N \hat{\sigma} \Delta_N D_{\Lambda/s}.$$

From the above one can easily conclude on the sources of the observed spin effects:

- hard subprocess asymmetries $\hat{a}$,
- spin dependence of structure functions $f_{a/\Lambda}$,
- spin dependent fragmentation functions $D_{h/c}$.

In general, factorization provides a powerful and transparent approach based on QCD Lagrangian to calculate the asymmetries to be then experimentally measured. What are the limitations of such predictions? The approach assumes a parton picture of hadron consisting of free quarks and gluons. In fact, only interactions with $Q^2 > \Lambda_\chi^2$, where Λ_χ is the scale for spontaneous breaking of chiral symmetry, should resolve the partonic structure. Perturbative QCD deals with perturbative vacuum invariant under the chiral transformations. But chiral invariance is not a symmetry of QCD. It is broken by the vacuum $< \bar{\Psi}_L \Psi_R > \neq 0$. This is why the range $\Lambda^2_{\mathrm{QCD}} < Q^2 < \Lambda^2_\chi$ requres more care.

At small distances $r < \Lambda_\chi^{-1}$ helicity is concerved due to chiral invariance. At $r > \Lambda^{-1}_{\mathrm{QCD}}$ there is no need for helicity conservation, but it appears that asymmetries in this range are close to zero. In the range between the two scales chiral symmetry is spontaneously broken and non-perturbative effects should be taken into account although α_s is small at $r < \Lambda^{-1}_{\mathrm{QCD}}$.

In the limit $m_q \to 0$ the QCD Lagrangian is invariant under the chiral group $SU(3)_L \times SU(3)_R$, and for massless quarks chirality and helicity coincide: $q_{1/2} = q_R, q_{-1/2} = q_L$. When $m_q = 0$ quark chirality is preserved under its interaction with gluons, W, Z and photons. Since $m_q \neq 0$, it allows to flip quark helicity without changing chirality. And suppression factor $m_q/\sqrt{Q^2}$ enters the parton level asymmetry

$$\hat{a}_N \propto \frac{\alpha_s m_q}{\sqrt{Q^2}}.$$

One-spin transverse asymmetry A_N for the hadron process should also vanish. This conclusion of perturbative QCD is confronted with the available experimental data. In particular,

a) for $p + p \to \Lambda_\uparrow + X$ polarization $P_\Lambda \neq 0$ does not depend much on energy, grows up and becomes constant at $p_\perp \simeq 1\mathrm{GeV/c}$;

b) in elastic $p_\uparrow p$-scattering the analyzing power $A \neq 0$ and grows with $p_\perp^2$;

c) for $p_\uparrow + p \to \pi^\pm + X$ the asymmetry $A_N \neq 0$ and expected to be large at $p_\perp > 1\mathrm{GeV/c}$.

The observed effects urge for further experimental studies. If the obtained results persist at higher energies it will strongly indicate for a nonperturbative origin of spin dynamics.

A study of $p_\perp$-dependence of one-spin asymmetries might be used as a way to reveal the transition from the non-perturbative phase ($A_N \neq 0$) to the perturbative phase ($A_N = 0$) of QCD. The very existence of such transition can not be taken for granted since there is a possibility that the vacuum, even at very short distances, is filled with fluctuations of gluon or quark fields [7]. The measurement of one-spin transverse asymmetries in this case would probe the chiral structure of the effective QCD Lagrangian.

Contrary to the above discussion the asymmetries $\hat{a}_{LL}$ and $\hat{a}_{NN}$ are large [8]. In this case the goal is to study the structure functions via the measurements of A_{LL} and A_{NN} parameters. Certainly, the question remains: are we in perturbative QCD sector to use the factorization formulas? The answer is "yes" if the measured $A_N = 0$. In the opposite case $A_N \neq 0$ one should estimate the sources of such effect and possibly to account for these sources under the analysis of two-spin asymmetries.

For inclusive processes all of the Fock states with arbitrary numbers of quarks and gluons and orbital angular momentum contribute to the equation for the structure functions. The conclusion is that hadron helicity should be represented as

$$\frac{1}{2} = \frac{1}{2}\Delta q + < L_z >_q + \Delta G + < L_z >_G,$$

where

$$\Delta G = \int_0^1 \Delta G(x) dx.$$

This is the gauge dependent equation for a hadron helicity distributed among its constituents. The study of spin effects in inclusive reactions will provide information on Composition of hadron spin, i.e. on the contributions of valence, sea quarks and gluons. One should note that the values of ΔG and $< L_z >_{q,G}$ in the above decomposition are gauge and frame dependent.

Up to now the major information on relative contributions to the hadron helicity is provided by Deep Inelastic Scattering processes' studies [1]. The object of interest are the two spin-dependent structure functions entering the cross-section difference

$$\begin{aligned}\frac{d^2\sigma(\overset{\rightarrow}{\leftarrow})}{dQ^2 d\nu} - \frac{d^2\sigma(\overset{\rightarrow}{\rightarrow})}{dQ^2 d\nu} &= \frac{4\pi\alpha^2}{Q^2 E^2}[M_N(E + E'\cos\Theta) g_1(\nu, Q^2) \\ &- Q^2 g_2(\nu, Q^2)].\end{aligned}$$

In Bjorken limit, when $Q^2 \to \infty$ and $x = Q^2/2M_N\nu$ is fixed

$$\begin{aligned}M_N^2 \nu g_1(\nu, Q^2) &\equiv g_1(x, Q^2) \to g_1(x), \\ M_N \nu^2 g_2(\nu, Q^2) &\equiv g_2(x, Q^2) \to g_2(x).\end{aligned}$$

The structure function g_1 is related to the polarized quark distributions

$$\begin{aligned}g_1^p(x) &= \frac{1}{2}\sum_q e_q^2 [q_{\rightarrow}(x) - q_{\leftarrow}(x) + \bar{q}_{\rightarrow}(x) - \bar{q}_{\leftarrow}(x)] = \\ &= \frac{1}{2}\sum_q e_q^2 (\Delta_L q + \Delta_L \bar{q}) = \frac{1}{2}\sum_q e_q^2 \Delta q(x).\end{aligned}$$

In naive parton model the first moment

$$\Gamma_1^p = \int_0^1 g_1^p dx = \frac{1}{18}(4\Delta u + \Delta d + \Delta s).$$

On the other hand, the data on neutron and hyperon beta decays lead to [9]

$$\Delta u - \Delta d = 1.2573 \pm 0.0028,$$

$$\frac{\Delta u + \Delta d - 2\Delta s}{\sqrt{3}} = 0.34 \pm 0.02.$$

And measurement of $g_1(x, Q^2)$ allows one to determine the particular spin distributions Δq. Experiments provide

$$\Delta q = \Delta u + \Delta d + \Delta s = 0.3, \quad \Delta s = -0.1.$$

Therefore, we have to conclude that

- about 2/3 of the proton spin belongs to gluons and orbital angular momentum,
- $\Delta s \neq 0$ and this fact, in particular, underlines the role of $\bar{q}q$-pairs in the nucleon structure.

In general, for the first moment one writes

$$\Gamma_1^p(Q^2) = \Gamma_\infty \left[1 + \sum_{n\geq 1} c_n \left(\frac{\alpha_s(Q^2)}{\pi}\right)^n\right] + \sum_{m\geq 1} \frac{b_m}{(Q^2)^m}$$

and respective corrections should be accounted under analysis of SMC ($\bar{Q}^2 = 10\mathrm{GeV}^2$) as well as SLAC ($\bar{Q}^2 = 3\mathrm{GeV}^2$) data.

The important test of QCD is related to verification of Bjorken sum rule

$$\begin{aligned}\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \frac{g_A}{6}\left[1 - \frac{\alpha_s(Q^2)}{\pi} + ...\right] &+ \frac{b_{p-n}}{Q^2} \\ -0.015 \geq b_{p-n} \geq &- 0.15\mathrm{GeV}^2,\end{aligned}$$

which has been obtained with account for isospin invariance and asymptotic freedom only. Available data on $g_1(x, Q^2)$ are quite agreeable with this equation.

The above conclusions on composition of the proton spin should be supplemented with few comments. Very first one is to be addressed to
<u>the Gluon Anomaly</u> (in the framework of pQCD interpretation). This phenomenon is related to nonconservation of axial vector current $J^0_{\mu 5}$:

$$s_\mu \Delta q =< p, s|J^0_{\mu 5}|p, s >=< p, s|\bar{q}_R\gamma_\mu q_R - \bar{q}_L\gamma_\mu q_L|p, s >,$$

$$J^0_{\mu 5} = \sum_q \bar{q}\gamma_\mu\gamma_5 q,$$

$$\partial^\mu J^0_{\mu 5} = \frac{3\alpha s}{4\pi} G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}, \quad m_q \to 0.$$

To ensure the conservation in the limit $m_q \to 0$ it was proposed to redefine the axial current

$$\tilde{J}^0_{\mu 5} = J^0_{\mu 5} - K_\mu, \quad \partial^\mu \tilde{J}^0_{\mu 5} = 0.$$

Matrix element of $\tilde{J}^0_{\mu 5}$ is to provide the true quark contribution into the proton spin [10]

$$\Delta q = \Delta\tilde{q} - \frac{3\alpha_s}{2\pi}\Delta G.$$

$\Delta\tilde{q}$ does not depend on Q^2. Besides that, $\Delta G \sim \ln Q^2$ at $Q^2 \to \infty$. It means that gluon contribution could be large to provide $\Delta\tilde{s} = 0$ and to return back to naive quark model describing static properties quite well. But [11] Q^2-independence of Δq is justified in pQCD only when chiral symmetry is preserved. It is also important that there is always non-perturbative gluon contribution. One must therefore conclude that predictive power of gluon anomaly is doubtful. In particular, the aspiration to get $\Delta s = 0$ does not have much sense in view of the data on criptoexotic baryon states [12]. Independent measurement of ΔG and Δs in polarized proton collisions at RHIC could try these arguments. It is also clear that one should find a way to account for non-perturbative effects at short distances, where experiments probe the hadron structure, and this structure in its turn shows up nontrivial Q^2 scale dependent features. The constituent quark model is associated with the long range interactions where it works quite successfully, in particular, describes static properties.

The other crucial aspect of the story is extrapolation of $g_1^p(x, Q^2)$ behaviour for the region of small x values used to extract $\Gamma_1^p(Q^2)$. Accepted "conservative" extrapolations are based on Regge pole like behaviour

$$g_1(x, Q^2) \sim x^{-\alpha_A(0)}, \quad \alpha_A(0) \leq 0.$$

On the other hand account for QCD evolution leads to the following dependence [13]

$$g_1 \propto \exp\left[c(Q^2)\sqrt{\ln\frac{1}{x}}\right],$$

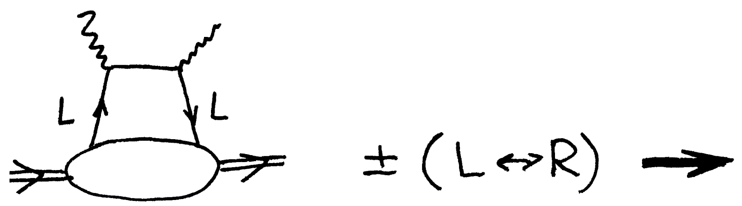
which is much steeper than the Regge-type parametrization provides. It is expected that this question will be answered under the experiments at "polarized" HERA dedicated to $g_1^p(x, Q^2)$ behaviour at $x \to 0$.

Enigma of the proton spin distribution should be experimentally solved at RHIC through the measurements of separate contributions of valence and sea quarks, gluons and angular momentum fraction.

The function $g_1(x,Q^2)$ is dominant contribution to the asymmetry in the case of longitudinally polarized nucleons. The structure function $g_2(x,Q^2)$ summarizes transverse spin effects in DIS. It is suppressed by factor of $O(Q^{-1})$ and includes terms $O(m_q/\sqrt{Q^2})$ which allow quark helicity to flip without changing chirality and terms $O(\Lambda_{\rm QCD}/\sqrt{\bar{Q}^2})$ arising from transfer quark helicity to gluons without changing chirality as well. The structure function g_2 may be represented as follows

$$g_2(x,Q^2) = g_2(x,Q^2)^{[2]} + g_2(x,Q^2)^{[3]},$$

where the first term is similar to g_1 and the second one appears from the twist-3 contribution and depends and quark masses. Simple parton interpretation of g_2 is impossible. It is interesting to note that preliminary data of E143 SLAC experiment are consistent with no twist-3 contribution. It is hard to measure the transverse spin effect in DIS because of the chiral invariance of electromagnetic current. Following ref.[14] we picture the chiral structure of the two distribution functions which can be measured in DIS



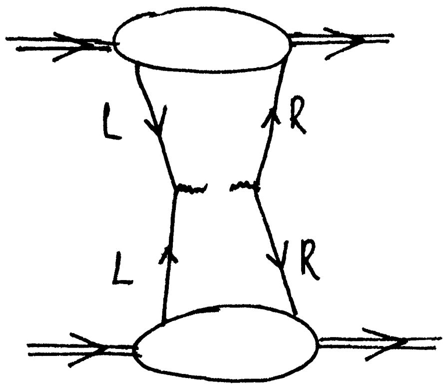
$f_1(x,Q^2)$

$g_1(x,Q^2)$

Chiral odd quark distribution

$h_1(x,Q^2)$

vanishes in perturbation theory because of chirality conservation at quark–gluon vertices in QCD. However in nonperturbative vacuum the condensate $< \bar{q}_L q_R > \neq 0$ violates the chiral symmetry. Therefore, there is a new structure function $h_1(x,Q^2)$ which measures the quark (for each flavor) momentum distribution in a transversely polarized nucleon weighted by ± 1 depending on how the quarks is polarized (parallel or antiparallel) to the nucleon. The function h_1 probes relativistic aspects of quark spin since $g_1 = h_1$ in nonrelativistic quark models. It provides dominant contribution in the transverse asymmetry for Drell–Yan processes $p_\uparrow + p_\uparrow \to \mu^+\mu^- + X$ $(\bar{q}+q \to \mu^+\mu^-)$.



$$A_{NN} = \hat{a}_{NN} \frac{\sum e_q^2 h_1^q(x_1) h_1^{\bar{q}}(x_2)}{\sum e_q^2 f_1^q(x_1) f_1^{\bar{q}}(x_2)}$$

It is assumed to study DY process with $\bar{q}q$ annihilation at RHIC with the two transversely polarized proton beams.

It has been already stressed that there is urgent need to include in the analysis of spin an account for non-perturbative effects, for instance, via the use of chiral models ideas [15]. The chiral symmetry breaking results, in particular, in generation of quark masses and appearance of quark condensates: $m_q \propto -\Lambda_\chi^{-2} < \bar{\psi}\psi >$. As a consequence it assumes some constraints on hadron structur e. A non-perturbative hadron appears as loosely bounded system of valence constituent quarks and quark condensate. Massive quarks appear as quasiparticles: as current quarks and the surrounding clouds of $\bar{q}q$-pairs consisting of a mixture of quarks of different flavors. We note that constituent quarks picture of a hadron is consistent with the results on the proton spin structure function g_1 obtained in DIS. The asymmetries in inclusive production are attributed to orbital motion of quark matter inside constituent quark. The origin of this orbital angular momentum could be traced from an analogy between hadron physics and superconductivity where pairing correlations induce particle current around the anisotropy direction. In our case the axis of anisotropy is determined by the polarization vector of valence quark located at the origin of constituent quark.

The relevant "laboratory" is the study of one-spin transverse asymmetries in pion production processes

$$p_\uparrow + p \to \pi^{\pm,0} + X :$$

- large A_N are expected at $p_\perp > 1\mathrm{GeV/c}$;
- it provides clean test of perturbative QCD; A_N might reveal transition between non-perturbative phase ($A_N \neq 0$) and perturbative one ($A_N = 0$);
- picture of a hadron may be cleared "through" non-perturbative analysis.

In conclusion we summarize the current expectations for spin physics at different laboratories (machines):

CERN (SMC)	$\vec{\mu}\vec{p}$	200 GeV	$\bar{Q}^2 = 10\text{GeV}^2$
SLAC	$\vec{e}\vec{p}$	50 GeV	$\bar{Q}^2 = 3\text{GeV}^2$

$$g_1^p, \quad g_1^p - g_1^n, \quad g_2(x, Q^2)$$

Q^2-dependence of g_1

HERA	$\vec{e}\vec{p}$	30 GeV	
	$\vec{e}\vec{p}$-collider		$x \leq 10^{-4}$ $15 < Q^2 < 3000\text{GeV}^2$
		$g_1, \quad g_2$	
	$pp_\uparrow$,	$\sqrt{s} = 40\text{GeV}$,	$p_\perp \leq 10\text{GeV/c}$
		A_N	
RHIC	$\vec{p}\vec{p}, p_\uparrow p_\uparrow$, $\Delta G(x), \quad \Delta q(x)$, $h_1(x, Q^2)$	$\sqrt{s} = 50 \div 500\text{GeV}$ $\Delta\bar{q}(x)$ with flavor separation	
NEPTUN	$p_\uparrow p, \vec{p}p$		

inclusive and elastic processes

LHC	search for compositeness (A_L) and supersymmetry (A_{LL})

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