Charmed proton spin

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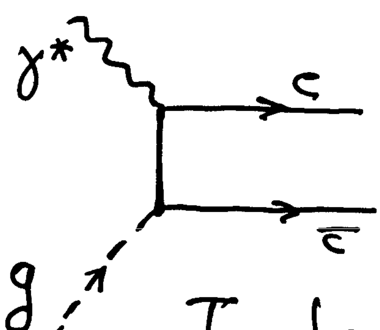
Proton spin crisis:

$$\Gamma_1^p \equiv \int_0^1 dx\, g_1^p(x) = 0.126 \pm 0.018$$

(EMC 1987)

$\Rightarrow$ (proton spin) $\neq \sum_{u,d}$ (valence quark spins)

Polarized sea-quark or/and gluons are needed. The gluon polarization $\Delta G(x)$ can be measured in the charm production.



$\leftarrow$ perturbative photon-gluon fusion mechanism (PGF)

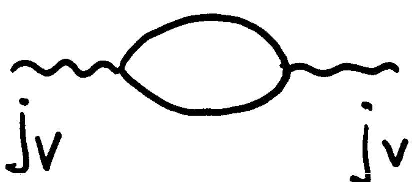
To be measured in

1). polarized $p\bar{p}$ collisions (RHIC, HERA-$\vec{N}$)
2) open charm production in polarized DIS (COMPASS experiment at LHC)

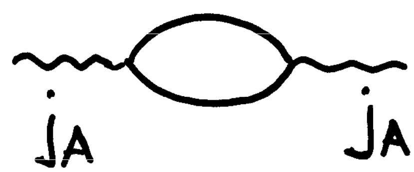
PGF <u>is</u> the dominant mechanism for unpolarized DIS. Should it be the case for polarized DIS? **Not necessarily!**

Axial and pseudoscalar channels are strongly influenced by nonperturbative effects.

<u>Example</u>:



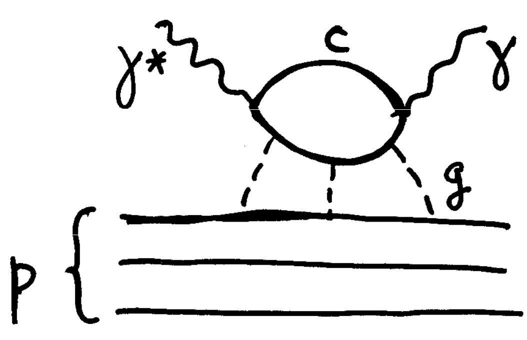
mixing is small,
the Zweig rule works well



mixing is 100 %,
nonperturbative breakdown of the Zweig rule

Charm can be produced <u>nonperturbatively</u> via DIS on the <u>intrinsic charm</u>

(**Brodsky** et. al. 80,81)



← (i) suppressed by $1/m_c^2$

(ii) no α_s suppression!

(iii) $\dfrac{IC}{PGF} \simeq 10$

Two estimates of intrinsic charm in proton:

1) Experimental evidence from <u>B-physics</u> (CLEO, 97)

$B \to \eta'$ decays $\Leftrightarrow \langle 0|\bar{c}\gamma_\mu\gamma_5 c|\eta'\rangle$ is large $\Leftrightarrow \langle p|\bar{c}\gamma_\mu\gamma_5 c|p\rangle$ IC component of the proton spin is large

2) Theoretical result: $\langle p|\frac{\alpha_s}{4\pi} G^a_{\mu\nu}\tilde{G}^a_{\mu\nu}|p\rangle$ is known (**Kühn, Zakharov 90**) $\Rightarrow$ one can find $\langle p|\bar{c}\gamma_\mu\gamma_5 c|p\rangle$ from the DIS data

<u>4 factors governing</u> $\Gamma_1^p = \int_0^1 dx\, g_1(x)$:

1). Spontaneous breaking of the chiral symmetry
2) a resolution of the $U(1)$ problem
3). the m.e. $\langle p|\frac{\alpha_s}{4\pi} G\tilde{G}|p\rangle$ - **KZ theorem (1990)**
4) the intrinsic charm component of the proton spin - extracted from the $B \to \eta'$ data.

SU(3) singlet proton spin from the data

We calculate $\Gamma_1^p(Q^2) \equiv \int_0^1 dx\, g_1(x, Q^2)$

The Operator Product Expansion gives

$$\Gamma_1^p(Q^2) = \frac{1}{2}\left(\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s + \frac{4}{9}\Delta c + \dots\right)\left(1 - \frac{\alpha_s(Q^2)}{\pi} + \dots\right)$$

where the quark components of the proton spin are

$$S_\mu \Delta q(Q^2) = \langle p|\bar{q}\gamma_\mu\gamma_5 q|p\rangle \quad , \quad q = u, d, s, c, \dots$$

proton spin vector

$$\left.\begin{aligned} \Delta u - \Delta d &\equiv g_A^3 \\ \Delta u + \Delta d - 2\Delta s &\equiv g_A^8 \end{aligned}\right\} \text{ can be found from the neutron and hyperon } \beta\text{-decays}$$

For $\Delta\Sigma \equiv \Delta u + \Delta d + \Delta s$ we obtain

$$\Gamma_1^p = C_{NS}(Q^2)\left(\frac{1}{12}g_A^3 + \frac{1}{36}g_A^8\right) + \frac{1}{9}C_S(Q^2)\left(\Delta\Sigma(Q^2) + 2\Delta c(Q^2)\right)$$

$$C_{NS}(S) = 1 - \frac{\alpha_s}{\pi} + \dots$$

A global fit to the data neglecting IC:

$\Delta u = 0.83 \pm 0.03$

$\Delta d = -0.43 \pm 0.03$

$\Delta s = -0.10 \pm 0.03$

$\Delta\Sigma = 0.31 \pm 0.07 \Rightarrow \boxed{g_A^0 \equiv \Delta\Sigma + 2\Delta c = 0.31 \pm 0.07}$

(Ellis & Karliner 95)

when IC is included

$(Q^2 = 10 \text{ GeV}^2)$

Taking the derivative, we obtain in the chiral SU(3) limit :

$$\frac{1}{2M_p\bar{p}i\gamma_5 p}\langle p|\underbrace{n_f\frac{\alpha_s}{4\pi}G\tilde{G}}_{\substack{\text{comes from}\\ u,d,s}}-\underbrace{2\cdot\frac{1}{16\pi^2 m_c^2}g^3G\tilde{G}G}_{\substack{\text{comes from IC contribution}\\ \Delta C}}|p\rangle = 0.31\pm 0.07$$

Technically, it is obtained using the OPE :

$$\partial_\mu(\bar{c}\gamma_\mu\gamma_5 c) = \frac{\alpha_s}{4\pi}G\tilde{G} + \overbrace{2m_c\bar{c}i\gamma_5 c}^{\text{OPE}}$$

$$= \frac{\alpha_s}{4\pi}G\tilde{G} - \frac{\alpha_s}{4\pi}G\tilde{G} - \frac{1}{16\pi^2 m_c^2}g^3G\tilde{G}G+\ldots$$

How to find contributions of SU(3) singlet for different flavors separately ?

$\Delta q' \equiv \Delta q + \frac{2}{3}\Delta C$ for $q=u,d,s$

can be taken from the Ellis-Karliner fit

On the other hand, take the derivative

$$\langle p|\, 2m_q\bar{q}i\gamma_5 q + \underbrace{\tilde{Q}}_{\text{SU(3) singlet part}}|p\rangle = \Delta q'\cdot 2M_p\bar{p}i\gamma_5 p$$

we cannot naively set $m_q=0$

SU(3) singlet part : $\tilde{Q} \equiv \frac{\alpha_s}{4\pi}G\tilde{G} - \frac{2}{3}\frac{1}{16\pi^2 m_c^2}g^3G\tilde{G}G$

(there are contributions due to goldstones with $m^2 \sim m_q$)

One can find $\langle p| m_q \bar{q} i\gamma_5 q |p\rangle$ for $q = u, d, s$ exactly in the chiral limit: Use

$$\begin{cases} \langle p| 2m_u \bar{u} i\gamma_5 u - 2m_d \bar{d} i\gamma_5 d |p\rangle = g_A^3 \cdot 2M_p \bar{p} i\gamma_5 p \\ \langle p| 2m_u \bar{u} i\gamma_5 u + 2m_d \bar{d} i\gamma_5 d - 4m_s \bar{s} i\gamma_5 s |p\rangle = g_A^8 \cdot 2M_p \bar{p} i\gamma_5 p \\ \langle p| 2m_u \bar{u} i\gamma_5 u + 2m_d \bar{d} i\gamma_5 d + 2m_s \bar{s} i\gamma_5 s |p\rangle = 0 \end{cases}$$

(no SU(3) singlet goldstone, the U(1) problem is solved)

$\Delta q'$:

$$\Rightarrow \langle p| 2m_u \bar{u} i\gamma_5 u |p\rangle = (0.725) \cdot 2M_p \bar{p} i\gamma_5 p \qquad (0.83)$$

$$\langle p| 2m_d \bar{d} i\gamma_5 d |p\rangle = (-0.532) \cdot 2M_p \bar{p} i\gamma_5 p \qquad (-0.43)$$

$$\langle p| 2m_s \bar{s} i\gamma_5 s |p\rangle = (-0.193) \cdot 2M_p \bar{p} i\gamma_5 p \qquad (-0.10)$$

$\Rightarrow$ the SU(3) singlet piece

$$\frac{1}{2M_p \bar{p} i\gamma_5 p} \langle p| \frac{\alpha_s}{4\pi} G\tilde{G} - \frac{2}{3} \frac{1}{16\pi^2 m_c^2} g^3 G\tilde{G}G |p\rangle \simeq 0.1$$

is the same for all the light flavors. It is small for each of $\Delta u, \Delta d, \Delta s$, but SU(3) variant parts cancel out in $\Delta\Sigma$ (the U(1) problem is solved)

Again : $(n_f = 3)$

$$\frac{1}{2M_p \bar{p} i\gamma_5 p}\langle p|\, n_f \frac{\alpha_s}{4\pi} G\tilde{G} - 2\cdot\underbrace{\frac{1}{16\pi^2 m_c^2} g^3 G\tilde{G}G}_{\text{IC contribution}}|p\rangle \simeq 0.3$$

How to find the second term ?

1) Use (Kühn & Zakharov, 90) (KZ)

$$\langle p|\, n_f \frac{\alpha_s}{4\pi} G\tilde{G}|p\rangle = -\frac{2n_f}{3b}\cdot 2M_p \bar{p} i\gamma_5 p$$

The first term in LHS is <u>negative</u> (KZ) !
We need the second term to make RHS positive.
We need

$$\frac{1}{2M_p \bar{p} i\gamma_5 p}\langle p| - \frac{1}{16\pi^2 m_c^2} g^3 G\tilde{G}G|p\rangle \simeq 0.3$$ - **twice larger than the first term**

2) Evidence for IC in the proton from B-physics:

$B\to\eta'$ decays $\Rightarrow$ IC component of η' is large

$$\langle 0|\bar{c}\gamma_\mu\gamma_5 c|\eta'(q)\rangle \equiv i f_{\eta'}^{(c)} q_\mu \;, \quad f_{\eta'}^{(c)} \simeq (100-120)\,\text{MeV}$$

is required by the data. Theoretically

$$f_{\eta'}^{(c)} \simeq \frac{3}{4\pi^2 b}\,\frac{1}{m_c^2}\,\frac{\langle g^3 G^3\rangle_{YM}}{\langle 0|\frac{\alpha_s}{4\pi} G\tilde{G}|\eta'\rangle} = O(\alpha_s^0)$$

How to find $\langle p|\bar{c}\gamma_\mu\gamma_5 c|p\rangle$ from $\langle 0|\bar{c}\gamma_\mu\gamma_5 c|\eta'\rangle$?

Use the Goldberger-Treiman like relation

$$\frac{1}{2M_p\,\bar{p}i\gamma_5 p}\langle p|-\frac{1}{16\pi^2 m_c^2}g^3 G\tilde{G}G|p\rangle = \underbrace{\frac{1}{2M_N}\underbrace{g_{\eta' NN}}_{=\,3-7} f_{\eta'}^{(c)}}_{=\,0.2-0.5}$$

in agreement with the previous estimate.

The <u>sign</u> and <u>magnitude</u> are what we need to explain Γ_1^p

$\Rightarrow$ IC gives the main contribution to the first moment $\Gamma_1^p = \int_0^1 dx\, g_1(x)$

Consequences for the charm production in DIS:

1). $\frac{PGF}{IC} = O(\alpha_s) \Rightarrow$ the charm production in polarized DIS will be overwhelmed by events due to IC mechanisms.

We expect an excessive production of open charm hadrons or S-wave quarkonia with low $p_\perp \sim m_c$

Beauty production: $\frac{m_b^2}{m_c^2} \simeq 10 \Rightarrow \frac{PGF(\text{charm})}{IB} \sim 1$

Summary

1) We face the same physics (intrinsic charm) in $B \to \eta'$ decays (CLEO) and polarized DIS experiments

2) IC component of the proton spin constitutes a main contribution to the first moment $\Gamma_1^p = \int dx\, g_1(x)$.
Its large magnitude is due to strong nonperturbative fluctuations in the axial SU(3) singlet channel.

3) Our scenario has very definite consequences for the charm production in polarized experiments and can be tested there.