The spin content of the nucleon sea

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The structure of the nucleon

Constituent Quarks

\[ Q^2 = 0 \text{ GeV}^2 \]

baryon octet
masses, magn. momenta

Parton Distributions

\[ Q^2 > 1 \text{ GeV}^2 \]

structure functions
momentum, spin
Surprises & Anomalies

about the Quark Structure of Nucleon: Sea

• Spin Structure: \[ \sum = \Delta u + \Delta d + \Delta s \approx 0.3 \]
  spin “crisis” or “puzzle”: where is the proton’s missing spin

• Flavor Asymmetry \[ \bar{u} \neq \bar{d} \]

• Strange Content \[ \Delta s \neq 0 \quad s(x) \neq \bar{s}(x) \quad ? \]
  Brodsky & Ma, PLB381(96)317

• Isospin Symmetry Breaking \[ \bar{u}_p \neq \bar{d}_n \quad \bar{d}_p \neq \bar{u}_n \quad ? \]
  or Charge Symmetry Violation
  Ma, PLB 274 (92) 111
  Boros, Londergan, Thomas, PRL81(98)4075
The Proton “Spin Crisis”

\[ \Sigma = \Delta u + \Delta d + \Delta s \approx 0.3 \]

In contradiction with the naïve quark model expectation:

**Naive Quark Model:**

\[ \Delta u = \frac{1}{3}; \quad \Delta d = -\frac{1}{3}; \quad \Delta s = 0 \]

\[ \Sigma = \Delta u + \Delta d + \Delta s = 1 \]
The Ellis-Jaffe sum rule & Its violation

\[ A_1^p = \int_0^1 dx g_1^p(x) = \frac{1}{2} \left[ \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right] \]

- Neutron beta decay and isospin symmetry
  \[ \Delta u - \Delta d = \frac{G_A^2}{G_V^2} = 1.261 \]
- Strangeness changing hyperon decay and SU(3) symmetry
  \[ \Delta u + \Delta d - 2\Delta s = 0.675 \]
- The assumption of zero strange spin contribution \[ \Delta s = 0 \]

The Ellis-Jaffe sum
\[ A_1^p = \int_0^1 dx g_1^p(x) = 0.198 \]

However, what EMC measured
\[ A_1^p = \int_0^1 dx g_1^p(x) = 0.126 \]
The first stage of experiments

- Non-zero strange spin contribution

\[ \Delta u = 0.750 \]
\[ \Delta d = -0.511 \]
\[ \Delta s = -0.218 \]

\[ \Sigma = \Delta u + \Delta d + \Delta s \approx 0.020 \]

A large negative strange spin contribution?
A previous global fit:

SU(3) symmetry+measured

\[
\begin{align*}
\Delta u & = 0.83 \pm 0.03 \\
\Delta d & = -0.43 \pm 0.03 \\
\Delta s & = -0.10 \pm 0.03
\end{align*}
\]

\[
\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3
\]

The second stage of experiments.
The third stage of experiments:

\[ g_1^p \quad g_1^n \quad \text{+semi-inclusive DIS process} \]

\[
\Delta u = 0.599 \pm 0.022 \pm 0.065 \\
\Delta d = -0.280 \pm 0.026 \pm 0.057 \\
\Delta s = 0.028 \pm 0.033 \pm 0.009
\]

\[
\Sigma = \Delta u + \Delta d + \Delta s \approx 0.347 \pm 0.024 \pm 0.040
\]

The strange contribution to the proton spin

\[ \Delta s \approx -0.2 \rightarrow -0.1 \rightarrow 0.03 \]

\[ \Delta s \neq 0, \text{ how large?} \]
The Strange-Antistrange Asymmetry

The strange quark and antiquark distributions are symmetric at leading-orders of perturbative QCD.

\[ s(x) = \bar{s}(x) \]

However, it has been argued that there is strange-antistrange distribution asymmetry in pQCD evolution at three-loops from non-vanishing up and down quark valence densities.

S. Catani et al. PRL93(2004)152003
Strange-Antistrange Asymmetry from Non-Perturbative Sources

• **Meson Cloud Model** \( s(x) < \bar{s}(x) \) at large \( x \)
  
  A.I. Signal and A.W. Thomas, PLB191(87)205

• **Chiral Field** \( s(x) > \bar{s}(x) \) at large \( x \)
  
  M. Burkardt and J. Warr, PRD45(92)958

• **Baryon-Meson Fluctuation** \( s(x) > \bar{s}(x) \) at large \( x \)
  
  S.J. Brodsky and B.-Q. Ma, PLB381(96)317
Mechanism for $s$-$s$-bar asymmetry
Phenomenological supports for s-sbar asymmetry

The nucleon strangeness asymmetry can explain a number of experimental observations:

- The NuTeV anomaly.  
  Y.Ding, B.-Q.Ma, PLB590 (2004) 216  
  Y.Ding, R.-G.Xu, B.-Q.Ma, PLB607 (2005) 101

- With heavy quark recombination to give a sizable influence on the measurement of the nucleon strangeness asymmetry in CCFR and NuTeV dimuon measurements.  

- The difference between Lambda and anti-Lambda spin transfers.  
  X.Du, B.-Q. Ma, PRD95 (2017) 014029
Prediction of s-sbar spin asymmetry

\[ \Delta s \neq \Delta \bar{s} \]

\[ \Delta s \approx -0.05 \text{ to } -0.01 \text{ and } \Delta \bar{s} \approx 0 \]
Nucleon strangeness polarization from $Λ/\bar{Λ}$ hyperon production in polarized proton-proton collision at RHIC

STAR results to indicate $\Delta s \neq \Delta \bar{s}$

$\Delta s \approx -0.025 \pm 0.019$

$\Delta \bar{s} \approx -0.001 \pm 0.012$
The STAR experiment at Relativistic Heavy Ion Collider (RHIC) is carrying out a spin physics program in high-energy polarized proton-proton collisions at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV.
Providing information about
• the inclusive production of hadrons
• the strange and antistrange quark polarizations of the proton.
Formalism

\[ A^{\Lambda/\bar{\Lambda}} = E_c \frac{\Delta d\sigma}{d^3 p_c} / E_c \frac{d\sigma}{d^3 p_c} \]

\[ E_c \frac{\Delta d\sigma}{d^3 p_c} (\text{AB} \rightarrow \text{C} + \text{X}) \]

\[ = \sum_{abcd} \int_{\bar{x}_a}^{1} dx_a \int_{\bar{x}_b}^{1} dx_b \Delta f_a^A(x_a, Q^2)f_b^B(x_b, Q^2) \]

\[ \Delta D_c^C(z_c, Q^2) \frac{1}{\pi z_c} \frac{\Delta d\hat{\sigma}}{d\hat{t}} (ab \rightarrow cd), \]
Parametrization of $\Lambda$ fragmentation functions

\[
D_d^\Lambda(x, Q^2) = D_u^\Lambda(x, Q^2)
\]
\[
= \left( \frac{D_u^\Lambda(x)}{D_{u+\bar{u}}^\Lambda(x)} \right)^{\text{th}} D_{u+\bar{u}}^{\Lambda}(x, Q^2)^{\text{AKK}}.
\]
\[
D_{\bar{d}}^\Lambda(x, Q^2) = D_{\bar{u}}^\Lambda(x, Q^2)
\]
\[
- \left( \frac{D_{\bar{u}}^\Lambda(x)}{D_{u+\bar{u}}^\Lambda(x)} \right)^{\text{th}} D_{u+u}^{\Lambda}(x, Q^2)^{\text{AKK}}.
\]
\[
\Delta D_d^\Lambda(x, Q^2) = \Delta D_u^\Lambda(x, Q^2)
\]
\[
= \left( \frac{\Delta D_u^\Lambda(x)}{D_{u+\bar{u}}^\Lambda(x)} \right)^{\text{th}} D_{u+\bar{u}}^{\Lambda}(x, Q^2)^{\text{AKK}}.
\]
\[
D_s^\Lambda(x, Q^2) = \left( \frac{D_s^\Lambda(x)}{D_{s+\bar{s}}^\Lambda(x)} \right)^{\text{th}} D_{s+\bar{s}}^{\Lambda}(x, Q^2)^{\text{AKK}},
\]
\[
D_{\bar{s}}^\Lambda(x, Q^2) = \left( \frac{D_{\bar{s}}^\Lambda(x)}{D_{s+\bar{s}}^\Lambda(x)} \right)^{\text{th}} D_{s+\bar{s}}^{\Lambda}(x, Q^2)^{\text{AKK}},
\]
\[
\Delta D_s^\Lambda(x, Q^2) = \left( \frac{\Delta D_s^\Lambda(x)}{D_{s+\bar{s}}^\Lambda(x)} \right)^{\text{th}} D_{s+\bar{s}}^{\Lambda}(x, Q^2)^{\text{AKK}}.
\]

X.Du, B.-Q. Ma, PRD95 (2017) 014029
Gluon to $\Lambda$ fragmentation functions

$$\Delta D_g^\Lambda(z, Q^2) = D_g^\Lambda(z, Q^2)\left(\frac{\Delta g^\Lambda(z, Q^2)}{g^\Lambda(z, Q^2)}\right)$$

assuming that the gluon polarization evolves in the same way between the octet baryons, i.e.,

$$\frac{\Delta g^\Lambda(z, Q^2)}{g^\Lambda(z, Q^2)} = \frac{\Delta g^p(z, Q^2)}{g^p(z, Q^2)},$$

Fitting to STAR DATA

\[ \alpha_3 = -2.17 \pm 1.65 \]

\[ \alpha_4 = -0.087 \pm 1.08 \]

Results from fitting STAR data

Table: Fitting results of $\alpha_i$ and calculated results of $\Delta s$ and $\Delta \bar{s}$.

<table>
<thead>
<tr>
<th>$\alpha_i$</th>
<th>value</th>
<th>$\Delta s$</th>
<th>$\Delta \bar{s}$</th>
<th>$\chi^2_{\text{min}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_1$</td>
<td>$-1.20 \pm 1.31$</td>
<td>$-0.014 \pm 0.015$</td>
<td></td>
<td>0.37</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>$-0.24 \pm 0.49$</td>
<td></td>
<td>$-0.003 \pm 0.005$</td>
<td>2.48</td>
</tr>
<tr>
<td>$\alpha_3$</td>
<td>$-2.17 \pm 1.65$</td>
<td>$-0.025 \pm 0.019$</td>
<td></td>
<td>0.42</td>
</tr>
<tr>
<td>$\alpha_4$</td>
<td>$-0.087 \pm 1.08$</td>
<td>$-0.001 \pm 0.012$</td>
<td></td>
<td>2.24</td>
</tr>
</tbody>
</table>

Two options: with/without gluon polarization
Comparison with Predictions & Results

The central values of the fitting results are basically compatible with

- the light-cone meson-baryon fluctuation model\textsuperscript{24} prediction $\Delta s(x) \approx -0.05$ to $-0.01$ and $\Delta \bar{s}(x) \approx 0$.
- the recent lattice QCD determination\textsuperscript{25}, $\Delta s^+ = -0.02(1)$ at $Q^2 \approx 7\text{GeV}^2$.
- the results from Jefferson Lab Angular Momentum (JAM) Collaboration\textsuperscript{26} $\Delta s^+(Q_0^2) = -0.03(10)$.

Feasibility of Strange Polarization Determination

Further improvement in precision can determine the strange-antistrange polarization asymmetry of the nucleon sea

Figure: Comparison of the symmetric and asymmetric input of polarized strange

Xiaonan Liu, B.-Q. Ma, EPJC 79 (2019) 409
Extraction of $u$-bar and $d$-bar polarizations

• The earlier unpolarized experiments confirmed the flavor asymmetry of light-flavor sea quarks:

$$\bar{u}(x) \neq \bar{d}(x)$$

• It is natural to speculate:

$$\Delta\bar{u}(x) \neq \Delta\bar{d}(x)$$

• We show that the $u$-bar helicity is positive and $d$-bar helicity is negative from RHIC $W$ asymmetry data:

$$\Delta\bar{u} > 0, \quad \Delta\bar{d} < 0$$
The flavor asymmetry of light-flavor sea quarks can be produced from an intuitive statistical model:

\[ \Delta \bar{u} > 0, \quad \Delta \bar{d} < 0 \]

There is also an asymmetry between antiquarks and quarks of the sea:

\[ \Delta q_s(x) \neq \Delta \bar{q}_s(x) \]

The valence part of spin structure can be well described by a light-cone quark-diquark model with the Melosh-Wigner rotation effect due to quark transversal motions.

B.-Q. Ma, PLB 375 (1996) 320
Conclusions

• The spin transfer process of $\bar{p}p \rightarrow \Lambda X$ is feasible to study strange-antistrange polarizations of the nucleon.

• The fitting to STAR data suggests: $\Delta s \neq \Delta \bar{s}$

$\Delta s \approx -0.025 \pm 0.019$

$\Delta \bar{s} \approx -0.001 \pm 0.012$

• The results are compatible with the light-cone baryon-meson fluctuation model prediction.
Happy Birthday to Stan!
Happy Birthday to Aram!