A few comments on the spin decomposition, and on recent developments at RHIC

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Probing Nucleons and Nuclei in High Energy Collisions
Institute for Nuclear Theory - Program 18-3
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What is a proton, neutron, nucleus anyway?

The proton is 2 up quarks and 1 down quark, ...

Really? “Just open many textbooks…”
What *is* a proton, neutron, nucleus?

**A high-energy view:** an unseparated, broadband beam of quarks, anti-quarks, and gauge bosons (primarily gluons), and perhaps other constituents, yet unknown.

40 years of an amazingly robust idealization:
Renormalization group-improved Parton Model

Factorization theorem(s) + one-dimensional parton distributions, no correlations among the partons

Really? More than a few of our high-energy observations are actually different
Essential to separate intrinsic structure from interaction dynamics,
push the envelope beyond the theoretically established,
obtain meaningful accuracy.
Really? - Proton spin

ELLIS-JAFFE SUM RULE


\[ \sigma(\Rightarrow, \Leftarrow) - \sigma(\Rightarrow, \Rightarrow) \sim g_1(x, Q^2) \]
Really? - Proton spin

\[ \Delta \Sigma \simeq 0.2, \Delta s < 0 \]

The sum of quark and anti-quark spins contribute little to the proton spin, and strange quarks are negatively polarized.
For the proton, 

\[ \Gamma_1 = \int_0^1 g_1(x)dx = \int_0^1 \left( \frac{1}{2} \sum e_q^2 \Delta q(x) \right) dx = \frac{1}{2} \left( \frac{4}{9} \Delta_1 u + \frac{1}{9} \Delta_1 d + \frac{1}{9} \Delta_1 s \right) \]

\[ = \frac{1}{12} (\Delta_1 u - \Delta_1 d) + \frac{1}{36} (\Delta_1 u + \Delta_1 d - 2\Delta_1 s) + \frac{1}{9} (\Delta_1 u + \Delta_1 d + \Delta_1 s) \]

which becomes a prediction if \( \Delta_1 s = 0 \)

No (reliable) substitute for energy; \( x \propto 1/\sqrt{s} \)
For the proton,

\[
\Gamma_1 = \int_0^1 g_1(x)dx = \int_0^1 \left( \frac{1}{2} \sum q^2 \Delta q(x) \right) dx = \frac{1}{2} \left( \frac{4}{9} \Delta_1 u + \frac{1}{9} \Delta_1 d + \frac{1}{9} \Delta_1 s \right)
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\]

Since,

\[
\left. \frac{\partial \Gamma_1}{\partial a_8} \right|_{\text{Ellis-Jaffe}} \approx \frac{5}{36} \quad \text{and} \quad \left. \frac{\partial \Gamma_1}{\partial a_8} \right|_{\text{experiment}} \approx 0
\]

\[\{\text{one can recover the E-J expectation with a sizable shift of } a_8 = 3F - D, \quad a_8 \simeq 0.2 \pm 0.1\}
\]

Really? - Proton spin

Known from weak neutron to proton decay, combined with weak $\Sigma$ to neutron decay

Unique to DIS, $\Delta \Sigma$
Numerous follow-up questions and experiment programs,

Among the early attempts at a resolution,

with the gluons \textit{polarized}.


Note: this attempt requires \textit{very} large polarization, \textit{factors} larger than the nucleon spin itself, and by inference, \textit{huge} compensating \textit{orbital momenta}. Quite the proton, a ground-state object and all.

Other attempts include e.g extrapolation over unmeasured low-\textit{x}. 
**DIS - Proton spin**

For the proton,

\[
\Gamma_1 = \int_0^1 g_1(x) dx = \int_0^1 \left( \frac{1}{2} \sum e_q^2 \Delta q(x) \right) dx = \frac{1}{2} \left( \frac{4}{9} \Delta_1 u + \frac{1}{9} \Delta_1 d + \frac{1}{9} \Delta_1 s \right)
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= \frac{1}{12} (\Delta_1 u - \Delta_1 d) + \frac{1}{36} (\Delta_1 u + \Delta_1 d - 2\Delta_1 s) + \frac{1}{9} (\Delta_1 u + \Delta_1 d + \Delta_1 s) + \mathcal{O}(\alpha_s) \text{ now well known } + \mathcal{O}(1/Q^2)
\]

\[
\checkmark < 10\%
\]

Similar can be done for the neutron,

experimentally via the deuteron or $^3$He,
For the proton,

\[ \Gamma_1 = \int_0^1 g_1(x)dx = \int_0^1 \left( \frac{1}{2} \sum e_q^2 \Delta q(x) \right) dx = \frac{1}{2} \left( \frac{4}{9} \Delta_1 u + \frac{1}{9} \Delta_1 d + \frac{1}{9} \Delta_1 s \right) \]

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\[ + \mathcal{O}(\alpha_s) \text{ now well known}\]

\[ + \mathcal{O}(1/Q^2) \]

Similar can be done for the neutron,

experimentally via the deuteron or \(^3\text{He},\)

Note, experimental precisions can straightforwardly be matched as can the (low) energies in fixed-target experiments.

Not so at a collider and looking ahead to EIC we should revisit the handling of nuclear effects.
World deuteron data, \( +\mathcal{O}(\alpha_s) \)

Neutron, from COMPASS d,p

\[
\int_{x_{\text{min}}}^{1} g_1^N \, dx
\]

\( Q^2 = 3 \, (\text{GeV/c})^2 \)

\[
\Gamma_1^{NS} = 0.192 \pm 0.007_{\text{stat}} \pm 0.015_{\text{syst}}
\]

\[
|g_A / g_V| = 1.29 \pm 0.05_{\text{stat}} \pm 0.10_{\text{syst}}
\]

\( \checkmark \)
\[ \Delta_1 u + \Delta_1 d - 2\Delta_1 s = 3F - D = 0.59 \pm 0.03 \]

Known from weak neutron to proton decay, combined with weak \( \Sigma \) to neutron decay

\[
\begin{array}{|c|c|c|c|c|}
\hline
\text{Channel} & f_1^{SU(3)} & |f_1V_{us}| & (g_1/f_1)^{SU(3)} & (g_1/f_1)^{\text{exp}} \\
\hline
n \to p & 1 & n/a & F + D & 1.2670(30) \\
\Lambda \to p & -\sqrt{3}/2 & 0.2221(33) & F + D/3 & 0.718(15) \\
\Sigma^- \to n & -1 & 0.2274(49) & F - D & -0.340(17) \\
\Xi^- \to \Lambda & \sqrt{3}/2 & 0.2367(97) & F - D/3 & 0.25(5) \\
\Xi^- \to \Sigma^0 & \sqrt{1}/2 & n/a & F + D & n/a \\
\Xi^0 \to \Sigma^+ & 1 & 0.216(33) & F + D & 1.32(22) \\
\hline
\end{array}
\]

A 1+1-experiment determination, more or less, with little hope of materially better data,

SU(3) breaking often largely ignored so far,

Renewed opportunity for lattice-QCD?
Note, *semi*-inclusive DIS data truly drive the DIS flavor decomposition.
Unique opportunities to study nucleon spin properties and spin in QCD,

**Longitudinal data**

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<tr>
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<th>STAR</th>
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<tbody>
<tr>
<td>2005</td>
<td>35 pb⁻¹</td>
</tr>
<tr>
<td>2006</td>
<td>50 pb⁻¹</td>
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<tr>
<td>2009</td>
<td></td>
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<th>√s = 500 GeV</th>
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<tr>
<td>2012</td>
<td></td>
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<tr>
<td>2013</td>
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**Transverse data**

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<td>2006</td>
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<tr>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>50 pb⁻¹</td>
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<tr>
<td>2015</td>
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</table>

<table>
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<th>√s = 500 GeV</th>
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</thead>
<tbody>
<tr>
<td>2011</td>
<td>25 pb⁻¹</td>
</tr>
<tr>
<td>2017</td>
<td>350 pb⁻¹</td>
</tr>
</tbody>
</table>

50-60% polarization

RHIC - Polarized Proton-Proton Collider
Gluon Polarization from RHIC

Gluon polarization is positive in the region of the data: $\Delta g \approx 0.2 \pm 0.1$
Gluon Polarization

Some properties of the DSSV polarized gluon:

DSSV, PRL 113, 012001(2014)

Easy to “hide” 1 h in the unmeasured region
Gluon Polarization

Some properties of the DSSV polarized gluon:

DSSV, PRL 113, 012001(2014)

- Strong impetus for better precision, via renewed measurement
- Sensitivity to underlying kinematics, via correlation (di-jet) measurement
- Sensitivity to smaller $x$, via 500 GeV data, forward acceptance

Easy to "hide" $1 \ h$ in the unmeasured region
Gluon Polarization

Some properties of the DSSV polarized gluon:

DSSV, PRL 113, 012001(2014)

The good news,

STAR is releasing (has released) a wealth of data addressing each of these aspects,

has a science-driven plan for forward instrument upgrades
(a talk in itself; truth in advertisement plan ≠ approval, at least not as of today).

Easy to “hide” 1 h in the unmeasured region
Gluon Polarization

An early glimpse in the forward acceptance region:

- Results are given for transverse momenta in the range $2 < p_T < 10$ GeV/c within two regions of pseudorapidity that span $2.65 < \eta < 3.9$

- These results are sensitive to the polarized gluon parton distribution function, $\Delta g(x)$, down to the region of parton momentum fraction $x \sim 0.001$

- These results will provide the first direct experimental constraints in $x \ll 0.01$

Correlation measurements will access larger (average) partonic asymmetries.
Gluon Polarization

Mid-central di-jet asymmetries:

Towards sensitivity to Bjorken-$x$.

Preliminary results at 500 GeV have come out as well, paper in preparation.
Gluon Polarization

**di-jet asymmetries in a more forward region:**

*Impact clearly exists; quantifying it will require renewed global analysis (and/or reweighting)*

PRD 98 (2018) 032011
Quark Polarization at RHIC

$\sqrt{s} = 500$ GeV above $W$ production threshold,

Experiment Signature:
large $p_T$ lepton, missing $E_T$

Experiment Challenges:
charge-ID at large $|\text{rapidity}|$
electron/hadron discrimination
luminosity hungry

Free of fragmentation (!)

Spin Measurements:

$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta \bar{d}(x_a)u(x_b)}{u(x_a)d(x_b) + d(x_a)u(x_b)} = \begin{cases} -\frac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \frac{\Delta \bar{d}(x_a)}{d(x_a)}, & x_b \to 1 \end{cases}$$

LO expressions to illustrate overall behavior,

NLO known and used in extracting pPDFs.
Quark Polarization at RHIC

See e.g. J. Zhang, INPC
Q.H. Xu, DIS

- Further confirmed the polarized sea asymmetry:
  \[ \Delta \bar{u} > \Delta \bar{d} \]
Beyond Quark and Gluon Spins

Theory may be ahead of experiment, although many questions remain,

Beautiful initial (DVCS) measurements from HERMES and JLab,

IMHO, very far from reliable insights on angular momentum parts in the (Ji) spin-decomposition,
Looking Ahead
Two orders in $x$ and $Q^2$ compared to existing data; few, if any, alternatives.
Conclusive insights in quark and gluon helicity from inclusive measurements, and orbital momentum by subtraction (!)
Also experimentally, we are still very far from a reliable decomposition of the proton spin

DIS data:

- small-x measurements provided the impetus for renewed study of the proton spin,

- data on proton and neutron targets over a wide x-range,
  confirming the Bjorken Sum rule,
  decent insight in the sum of quark and anti-quark spins,

- initial sensitivities to scale dependence,

- best (lack of?) insight in strangeness,

- start of DVCS measurements with sensitivity to orbital momentum

RHIC spin program:

- has achieved the most sensitive insights in **gluon polarization** in the nucleon,
  *gluons are positively polarized for momentum fractions x > 0.05,*
  *at the level of 0.2 h for Q^2 = 10 GeV^2*

- has provided evidence, with measurements at the W-mass scale that are free of fragmentation uncertainties, of non-perturbative **sea-quark polarization**, 

- (quite promising TMD measurements; again a talk by itself)

**EIC + theory will be essential to arrive the spin decomposition (or at least a partial one).**