Central Questions in Nucleon Structure

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BNL Nuclear Theory

Presented by
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Exploring the nucleon:
Of fundamental importance in science

Know what we are made of!

Explore and Understand QCD:
Lattice, Models

Test our ability to use QCD:
Asymptotic Freedom, Factorization

Nucleon as tool for discovery:
RHIC Heavy Ions, LHC Tevatron High-$E_T$ jets NuTeV anomaly, ...
We can probe the quark-gluon structure of the Nucleon in short-distance processes:

- Diverse probes: DIS, DVCS, Drell-Yan, pp→jetX, ...
Questions to ask:

- What are the momentum distributions of quarks, anti-quarks, and gluons? \( p = x P \)
- What flavor symmetries hold-- or how are they broken? \( \bar{u} \) vs. \( \bar{d} \) \( s \) vs. \( \bar{s} \)? Isospin-symmetry between \( p \) and \( n \)?
- How are quarks and gluons distributed spatially?
- How do partons carry the proton spin-1/2? (Spins & orbital angular momenta)
- What difference does \( \rightarrow \) vs. \( \uparrow \) make? What novel features arise?
- How are quarks and gluons correlated?
These are central questions of the field.

The challenge is: Map out the Nucleon

Its complete spin, flavor, gluon landscape

- We have a pretty good picture of some aspects
- We are learning about others
- We are still in the dark in many cases

We’ll have a good chance to get all the answers with present and next-generation facilities!
Momentum distributions of quarks and gluons
- An important part of our picture of the nucleon: Gluons rule at small-$x$!

- We know a lot, but ...
• but ... some aspects little understood, for example:

  sea quarks and gluon at high-x, valence at very-high-x

  Testing ground for models of Proton wave function
  Measure at Jlab-12 GeV
  sea: DY

  Not an academic problem: LHC
  Measure at HERA, EIC
\[ F_L \propto \frac{\alpha_s}{2\pi} x \int_x^1 \frac{d\xi}{\xi} \xi (1 - \xi) g \left( \frac{x}{\xi}, Q^2 \right) + \ldots \]

One observable among many: \( \frac{dF_2}{d\log(Q^2)} \), \( ep \rightarrow \text{jet+jet+X} \), charm, ...
Helicity structure of the Nucleon

\[ \Delta q(x) = \text{Diagram 1} - \text{Diagram 2} \]

\[ \Delta g(x) = \text{Diagram 3} - \text{Diagram 4} \]
A major motivation: Explore the proton spin!

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

\[ \frac{1}{2} \int_0^1 dx [\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}] \]

\[ \int_0^1 dx \Delta g(x) \]

"Quotable" properties of the proton

q+q spin contribution

Gluon spin contribution

Orbital ang. momenta
• Rests on a number of things:
  
  • small-x extrapolation of structure function
  
  • at small-x, typically $Q^2$ small as well. Higher twists?

  To really nail it down, need measurements at lower $x$.
  And: at current $x$, but higher $Q^2$ \( \rightarrow \) EIC

• use of SU(3) symmetry:

\[
\int_0^1 dx \ g_1 = \frac{1}{9} \Delta \Sigma + \frac{1}{12} \left[ \Delta u + \Delta \bar{u} - \Delta d - \Delta \bar{d} \right] + \frac{1}{36} \left[ \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} - 2(\Delta s + \Delta \bar{s}) \right]
\]

\[
g_A = 1.257 \pm \ldots
\]

\[
3F - D = 0.575 \pm 0.05
\]

\textbf{Bjorken}
• if all true, current picture is:

\[
\frac{1}{2} \frac{\hbar}{\Delta u + \Delta \bar{u}}
\]

\[
\frac{1}{2} (\Delta s + \Delta \bar{s})
\]

\[
\frac{1}{2} (\Delta d + \Delta \bar{d})
\]

• is it correct?

• would like to know more: \( \Delta \bar{u} \) vs. \( \Delta \bar{d} \) vs. \( \Delta \bar{s} \) etc.
• **Important applications for models:**

\[ |\vec{p}| = \langle u \uparrow | u \uparrow \rangle + \langle u \uparrow | u \uparrow \rangle + \langle d \downarrow | d \downarrow \rangle + \ldots \]

Many models predict \( \Delta \bar{u} > 0 \) \( \Delta \bar{d} < 0 \)

Thomas, Signal, Cao; Holtmann, Speth, Fässler; Diakonov, Polyakov, Weiss; Glück, Reya; Schäfer, Fries; Kumano; Wakamatsu; ...

Various avenues for addressing these questions
At RHIC:

$$A_{L}^{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

unpol.

- $W$+charm at RHIC-II
In lepton scattering: “SIDIS”

- Major topic at Jlab-12 GeV
EIC:

J. Seele

- also, at EIC:

\[ \sin^2(\Theta_W) ? \]
• Bjorken’s sum rule

\[
\int_0^1 dx \, g_1^{ep-en}(x, Q^2) = \frac{1}{6} \frac{g_A}{g_V} \left\{ 1 - \frac{\alpha_s(Q^2)}{\pi} - \frac{43}{12} \frac{\alpha_s^2(Q^2)}{\pi^2} - 20.215 \frac{\alpha_s^3(Q^2)}{\pi^3} \right\}
\]

high-order perturbation theory

\[
+ \frac{M^2}{Q^2} \int_0^1 x^2 \, dx \left\{ \frac{2}{9} g_1^{ep-en}(x, Q^2) + \frac{1}{6} g_2^{ep-en}(x, Q^2) \right\}
\]

target-mass corrections

\[
- \frac{1}{Q^2} \frac{4}{27} F^{u-d}(Q^2)
\]

Twist-4 matrix elements \( \sim \langle \bar{q} \tilde{F} q \rangle \)

• Precision QCD. Currently tested at \( \sim 10\% \).
Can it be tested at \( \sim 1 \) or \( 2\% \)?

See Antje Bruell’s talk next
The gluon spin distribution $\Delta g$

Not much information until recently:

$$\frac{d g_1}{d \log(Q^2)} \propto \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x, Q^2) + \text{quark contrib.}$$

Bag model Chen, Ji $\Delta G \approx 0.3$

$\Delta G \approx 1.8 \text{ (at } 1\text{GeV}^2)$

“axial anomaly” Altarelli et al.

$\Delta G \approx 0.4$

$\Delta G \approx -1.7$
• NOW:

\[ \Delta g = -g, \Delta g = 0 \]

HERMES, COMPASS

jet(s), c\bar{c}, ...

GRSV-max

PHENIX Preliminary
- Run5 Photon Trigger
- Run6 Photon Trigger, high \( p_T \)

Scaling error of 40% is not included.
Challenge will be to really extract $\Delta g$ and its integral:

$$\Delta \sigma = \sum_q \int dx_g \int dx_q \Delta g(x_g, p_T) \Delta q(x_q, p_T) \Delta \hat{\sigma}^{gq}(x_g, x_q, p_T, \alpha_s(p_T)) + \ldots$$

→ Need “Global analysis”

Eventually, for integral will likely need additional information, in particular from smaller $x$

$Q^2 = 5$ GeV$^2$

~ RHIC 200 GeV midrap. data
- RHIC at 500 GeV, and with jet+jet, gamma+jet at forward kinematics
- An Electron-Ion Collider!
\[
\frac{d g_1}{d \log(Q^2)} \propto - \Delta g(x, Q^2) \quad \text{at small } x
\]
What’s the structure of a Transversely polarized Nucleon?
Transversity:

\[ \delta q(x) = \uparrow - \downarrow \]

- in helicity basis:

\[ \delta q(x) \sim \]

Helicity-flip!

Ralston, Soper; Jaffe, Ji; ...
• **the physics involved:**

* “odd chirality” $\rightarrow$ helicity-flip, $\chi_{\text{SB}}$

* no mixing with gluons

* tensor charge

$$
\langle \mathbf{P} | \bar{\mathbf{q}} i \sigma^{\mu\nu} \gamma^5 \mathbf{q} | \mathbf{P} \rangle = \int_0^1 dx \left[ \delta \mathbf{q}(x) - \delta \bar{\mathbf{q}}(x) \right]
$$

* difference to helicity probes relativistic / dynamical effects
• **Opportunities for measurement?**

* not in inclusive DIS, but:

\[ \pi \rightarrow \text{azimuthal asym.} \]

* this effect actually appears to be there: HERMES
• information on Collins fragm. fct. has become available from BELLE in $e^+e^- \rightarrow \pi\pi X$

→ First glimpse of Transversity!

(Anselmino et al.)
The future of transversity:

- **SIDIS at** COMPASS, Jlab-12 GeV
- **Collins-type asymmetries at** RHIC
- **Drell-Yan:**

  ![Diagram](image)

  - RHIC / RHIC-II
  - GSI, J-PARC

- **azimuthal asymmetries in SIDIS at** EIC
Transverse spin offers further new insights into Nucleon structure.

\[ \text{correlation} \sim \vec{S}_T \cdot \left( \vec{P} \times \vec{k}_T \right) \]

Sivers
Where would this show up?

\[ e p^+ \rightarrow e \pi X \]

\[ \sin(\phi - \phi_S) \sum_q c_q^2 f_{1T}^{q}(x) D_q(z) \]

SMC, HERMES, COMPASS, CLAS

Seen!
In pp scattering: involved (in disguised form) in large "left-right" asymmetries

\[ A_N = \frac{L - R}{L + R} \]
What’s the physics of the Sivers functions?

- Involves orbital angular momentum
- $T$-invariance of QCD: they involve a “rescattering” in the color field of the remnant

Probes overlap of proton wave fcts. with $J_z = \pm 1/2$

Brodsky, Hwang, Schmidt; Collins; Belitsky, Ji, Yuan; Boer, Mulders, Pijlman

Attractive!
• profound physics implication:
  \[ \rightarrow \text{process-dependence of Sivers functions} \]

**DIS:** “attractive”  
**DY:** “repulsive”

\[ \text{Sivers}_{\text{DIS}} = -\text{Sivers}_{\text{DY}} \]

• hugely important in QCD -- tests much of what we know about description of hard processes
Many avenues for important measurements:

- Drell-Yan
  RHIC / RHIC-II
  GSI, J-PARC

- correlations in pp$\rightarrow$jet+jet X at RHIC (now data!)

- detailed studies of azimuthal asymmetries in SIDIS at EIC at high $Q^2$
What’s the spatial structure of the Nucleon?
Over the last decade, theory has understood that parton distributions and form factors are special cases of a much more powerful representation of nucleon structure: "Generalized Parton Distributions"

Müller, Robaschik; Ji; Radyushkin

- $x$: average quark momentum fraction
- $\xi$: "skewing parameter" = $x_1 - x_2$
- $t$: 4-momentum transfer squared
What we dream of:

Tomographic images of the nucleon:

\[
\int d^2 \Delta_{\perp} e^{-i \Delta_{\perp} \cdot b_{\perp}} H_q(x, \xi = 0, -\Delta_{\perp}^2) = q(x, b_{\perp})
\]

At EIC: spatial distribution of sea and glue
• Quantify orbital motion of partons in nucleon

\[ J_q = \frac{1}{2} \lim_{t \to 0} \int dx \, x \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right] \]

\[ = \frac{1}{2} \Delta q + L_q \]

GPDs have potential to take our picture of the nucleon to a new level.
HE setup: $e^{+/−}$ (10 GeV) + p (250 GeV)  
L = $4.4 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$  
38 pb$^{-1}$/day

LE setup: $e^{+/−}$ (5 GeV) + p (50 GeV)  
L = $1.5 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$  
13 pb$^{-1}$/day

Precision of DVCS unpolarized cross sections

\[ \langle Q^2 \rangle = 10.4 \text{ GeV}^2 \]

Projected results

• also: gluon imaging with exclusive $J/\Psi$

Frankfurt, Strikman, Weiss
The challenge is: Map out the Nucleon
Its complete spin, flavor, gluon landscape

We’ll have a good chance to get all the answers with present and next-generation facilities!
http://www.bnl.gov/eic

All NSAC 2007 White/Position Papers Associated with EIC

- EIC White Paper (Draft April 4)
- eA Position Paper (Final)
- GPD White Paper, Summary of GPD WS at Maryland (January 2007)
- eRHIC Accelerator Position Paper (BNL) (Final)
- eLIC ZDR Version (January, 2007)